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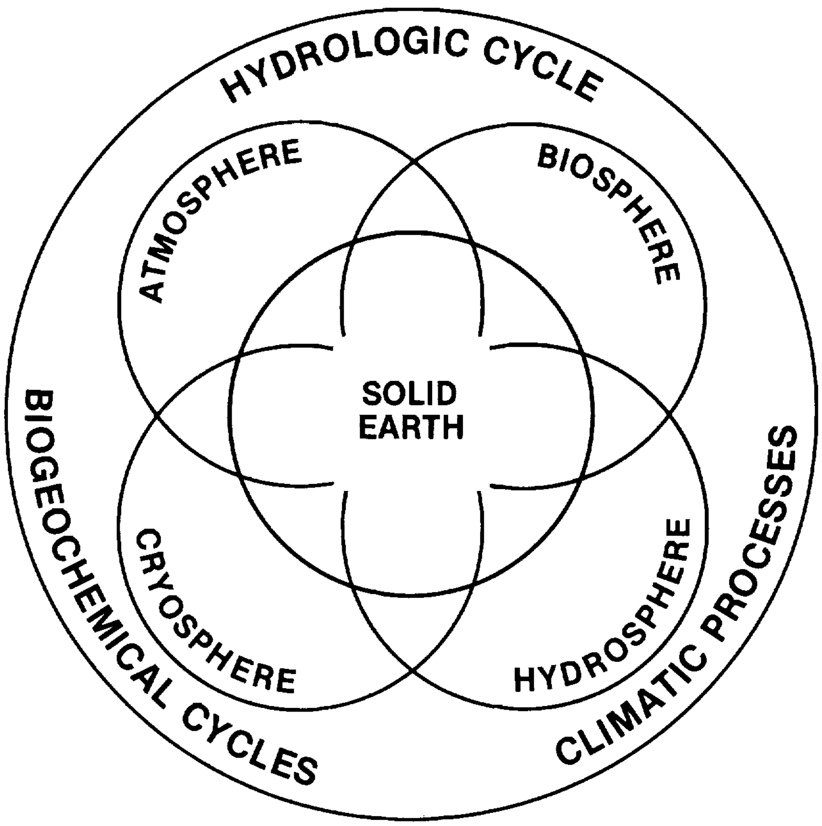
EARTH OBSERVING SYSTEM



Science and Mission Requirements
Working Group Report

Volume I (Appendix)

NASA

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APPENDIX: SCIENTIFIC BACKGROUND

Contents

GLOBAL HYDROLOGIC CYCLE

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SCIENTIFIC OBJECTIVES FOR THE 1990s

The global hydrological cycle has been characterized as a gigantic distillation scheme that is a major part of the Earth's heat engine. The cycle exists because the unique position of the Earth in the solar system allows for a temperature regime that permits water to exist in its three phases: solid, liquid and vapor. It is the transfer of water between these three phases among the land, oceanic and atmospheric reservoirs that is important in energy transport around the Earth. It is clear that the mechanisms of the atmospheric circulation are strongly coupled to the components of the hydrological cycle and that one cannot be studied meaningfully without the other. In addition to the transfer of energy around the Earth these water fluxes are important in sedimentation processes and the transport of trace elements.

The primary reason for studying the hydrological cycle or world water balance is not this connection with the atmospheric circulation, however, but rather that neither plant nor animal life can exist on Earth in the absence of water. Therefore it is important for us to understand the hydrological cycle and the spatial and temporal variations of the principal storage reservoirs of fresh water on the Earth's surface. Up to now only crude estimates of the amount of water in storage have been possible. Of all the water on the Earth's surface only approximately 3% is fresh water and of the fresh water about 77% is locked up in the polar ice caps or glaciers and 22% is in ground water. The remaining 1% of fresh water is split up amongst storage on land as snow or soil moisture, fresh water lakes and rivers, and water vapor. Of these three components, it is the first (snow and soil moisture) which probably has the greatest variability. Fortunately, there now is the possibility of quantitatively making observations of these quantities with the assistance of remote sensing. An improved understanding of the global hydrologic cycle will result.

Soil Moisture and Evapotranspiration

There are certain scientific questions important to understanding the hydrologic cycle on various scales. What are the nature and dynamics of worldwide soil moisture variations? Can remotely-sensed observations of surface soil moisture make a contribution to improved understanding of soil water movement, and are the surface observations related to variations in the soil moisture profile? Can regional and global evapotranspiration be determined from satellite observations of surface temperature, land cover, soil moisture, and albedo? What effects do soil moisture and evapotranspiration variations have on atmospheric circulation, food production, streamflow, and global water supply?

The importance of soil moisture relates to its effect on the partitioning of precipitation into runoff and infiltration components, of solar radiation into latent and sensible heat components at the land-air boundary, and as a major element in the growth of vegetation and global food production. Evapotranspiration is vital to crop growth while protecting the plant from overheating. Evapotranspiration also returns approximately 60-80% of precipitation falling on the earth to the atmosphere where it becomes the source for future precipitation. Both of these parameters are extremely difficult to measure. New techniques (including remote sensing) need to be developed to determine soil moisture storage and evapotranspiration at scales ranging from fields to continents.

Precipitation

There are certain scientific questions to be answered related to precipitation that are important not only because precipitation is the major driving force in the hydrologic cycle, but also because it is of major significance in meteorology and agriculture. What are the distribution and magnitude of precipitation over land as well as ocean areas? Can precipitation processes be observed and measured over areas ranging from small basins (~100 km^2) to continental areas? What effects do changes in precipitation patterns and amounts have on water supply, food production, and atmospheric circulation?

The importance of precipitation is related to the fact that it is the major input of water to both the land and ocean parts of the hydrologic cycle. It is also a major forcing function in climate processes. In agriculture it is a critical element for crop production. As evidence of its importance for man, the overabundance or marked deficiency of precipitation can have catastrophic effects, namely, flooding and drought.

The major investigative effort will be to see if remote sensing capabilities can be effectively combined with existing ground-based rain gauge networks and meteorological radar to conclusively measure areal precipitation characteristics. It is a job that cannot be done by conventional techniques alone.

Snow Cover

In cold regions of the world, stored precipitation in the form of snow has a major effect on the timing of runoff in the hydrologic process. Major scientific questions include what are the nature and dynamics of the world-wide snow cover? Can key snow-cover characteristics (extent, depth, water equivalent, wetness) be reliably measured over large areas? What effects do changes in snow cover have on global water supply, atmospheric circulation, and food production?

Improved knowledge of snow cover is important because the volume of water stored as snow affects forecasts of water supply and flooding, crop planting selection and strategy, irrigation, and management of agricultural commodities and surpluses. Snowmelt is the major component of the total annual water supply in large parts of the world. The snow-cover extent over large areas and the trends of snow coverage over extended time periods are of particular interest to hydroelectric power companies (in snow regions) who must make decisions on whether to invest in the development of additional power generating facilities. Because of snow's high albedo and variable areal extent, its presence or absence can drastically alter the energy budget and surface temperature. Knowledge of snow's properties is vital for improving medium and long range weather forecasts and for perfecting general circulation models.

Hydrologic Model Interfacing

One of the major scientific questions in hydrology is: Can remote sensing data be used effectively with models to improve our understanding of hydrologic processes? Virtually all hydrologic models, with only a few exceptions, have been designed to interface with conventional point data. These models must be modified or new ones developed to be compatible with remote sensing capabilities (areal coverage, high spatial resolution, repetitiveness, etc.). A comprehensive program of development and testing of these models at various application scales ranging from flash flood modeling and small tributary streams to continental size general circulation models must be carried out.

Key Scientific Hydrology Research Problems for the 1990s

1. Development of new techniques for determination of soil moisture storage and evapotranspiration at scales ranging from fields to continents.
2. Quantitative assessment of precipitation amount and distribution over drainage basins.
3. Worldwide monitoring of snow cover extent and water equivalent in both mountain and flat land areas.
4. Development and testing of comprehensive hydrologic models designed to be compatible with remote sensing capabilities (high resolution, areal coverage, repetitiveness) at various application scales ranging from flash flooding on small tributary streams to general circulation models.
5. Quantification of the components and improved understanding of the global hydrologic cycle.

OBSERVATIONAL REQUIREMENTS

Soil Moisture

In monitoring soil moisture, the three major data set parameters needed are (1) soil moisture content in the upper layer of the soil, (2) surface temperature, and (3) vegetation type and biomass. Table A1.a presents some of the resolution requirements and area coverage. The soil moisture observations require repetitive coverage every 1-3 days and an all-weather soil moisture measurement capability. Some possible generic sensors for acquiring the data are: 21 cm passive microwave radiometer (scanning) with 10 km resolution; 6 cm active radar, 10° - 20° incidence angle with 100 m resolution for sampling; and AVHRR-type sensor with 1 km res-

TABLE A1.a. Observational Needs for Soil Moisture Monitoring

		Data set resolution (averages)		Observation resolution	
Data set parameter	Area coverage	Horizontal Scale	Time	Horizontal Scale	Frequency
1. Soil moisture content	a. Sub-continental, variable surface cover	10 km	3d	10 km	1-3d
	b. Irrigation district	1 km	3d	0.1 km	1-3d
2. Surface temperature	Sub-continental, variable surface cover	10 km	3d	1 km	daily
3. Vegetative type biomass	Sub-continental, variable surface cover	10 km	weekly	1 km	3d

olution; thermal infrared for surface temperature and vis/near IR for vegetation mapping. The measurements should have a swath width of 1000 km and should be made from a polar, sun-synchronous orbit having equator crossings at 2:00 a.m. and 2:00 p.m.

Evapotranspiration

The observational requirements for evapotranspiration are similar to those for soil moisture. There may be a need for more detailed measurements on small test areas, hence the need for a high resolution, multispectral sensor. The specific resolution requirements are listed in Table A1.b. Some possible generic sensors for evapotranspiration observations are: MLA-type instrument with visible, near infrared, and thermal capability for detailed studies; AVHRR-type instrument with 1 km resolution for large area studies; and 21 cm passive microwave radiometer (scanning) with 10 km resolution. Repetitive coverage of the observations is required every day and should be obtained from a polar, sun-synchronous orbit having equator crossings at 2:00 a.m. and 2:00 p.m.

Precipitation

Observations of various data set parameters associated with precipitation pose generally more difficult requirements because of the need of much more frequent observations. It may be that such a problem should be attacked from a geosynchronous platform, although it is definitely possible from a polar orbiting system (which may mean more than one satellite). Precipitation can be measured using cloud observations with visible and near infrared data or by directly sensing the rainfall using microwave techniques. It may also be possible to improve rainfall measurement by the frequent monitoring of soil moisture as outlined previously. Table A1.c outlines the resolution and area coverage requirements. Suggested methods for measuring precipitation include a passive microwave system for use over oceans at very short wavelengths, a space borne meteorological radar instrument with a 1 km resolution, a high spatial resolution (1 km) visible and infrared radiometer, as well as detailed ground truth networks in several study areas. The observations should be made twice daily for a period of several days (additional observations from multiple satellites) from afternoon and early morning overpasses.

Snow Cover

In observations of snow cover, three major parameters are required - areal extent, water equivalent or depth, and liquid water content. The latter may be used for improving the timing of snowmelt runoff forecasts or for refining the water equivalent estimates. Table A1.d presents the resolution requirements. Repetitive coverage of the observations is required every 3-5 days with an all weather measurement capability. Generic instruments for these measurements include: a multichannel microwave radiometer at Ka, Ku, and X bands providing 1-5 km resolution; an active radar at 0.8-2.0 cm wavelength with a 200-400 m resolution; and an MLA-type instrument with visible, near infrared, and thermal capability. The measurements should be made from a sun-synchronous orbit to provide long-term, constant illumination observations.

TABLE A1.b. Observational Needs for Evapotranspiration Estimation

		Data set resolution (averages)		Observation resolution	
Data set parameter	Area coverage	Horizontal Scale	Time	Horizontal Scale	Frequency
1. Soil moisture	a. Sub-continental, variable surface cover	10 km	3d	10 km	1-3d
	b. Irrigation district	1 km	3d	0.1 km	1-3d
2. Surface temperature	Sub-continental, variable surface cover	10 km	3d	1 km	daily
3. Vegetation type	Sub-continental, variable surface cover	10 km	weekly	1 km	3d
4. Albedo	Sub-continental, variable surface cover	10 km	3d	1 km	3d

TABLE A1.c. Observational Needs for Precipitation Monitoring

Data set parameter	Area coverage	Data set resolution (averages) Horizontal Scale	Data set resolution (averages) Time	Observation resolution Horizontal Scale	Observation resolution Frequency
1. Precipitation rate	a. Sub-continent	1 km	2/d	1 km	2/d
	b. Oceans	50 km	daily	5 km	daily
2. Precipitation amount	a. Sub-continent	1 km	daily	<1 km	daily
	b. Continents and oceans	1-4 km	daily	1-4 km	<1 hr

TABLE A1.d. Observational Needs for Snow-Cover Dynamics

Data set parameter	Area coverage	Data set resolution (averages) Horizontal Scale	Data set resolution (averages) Time	Observation resolution Horizontal Scale	Observation resolution Frequency
1. Areal extent	Mountainous western United States	200 m	weekly	100 m	3-5d
2. Water equivalent (depth)	a. Sub-continental, variable surface cover	1-5 km	weekly	1-5 km	3-5d
	b. Subset of sub-continental area	1-5 km	weekly	500 m	3-5d
3. Liquid water content (wetness)	a. Sub-continental, variable cover type	1-5 km	weekly	1-5 km	3-5d
	b. Subset of sub-continental area	1-5 km	weekly	500 km	3-5d

GLOBAL BIOGEOCHEMISTRY AN OVERVIEW

Berrien Moore III

With water and oxygen four elements—carbon, nitrogen, phosphorus and sulfur—are of special interest in the study of global cycling. As with all elements, each of these four follows a path through the biosphere that is determined partly by its biogeochemical properties. Although in this sense, each element has a "natural cycle," human activity has significantly altered some of them: certain indicators of the state of particular cycles, for example the level of atmospheric CO_2, have moved well outside their historical distributions.

The effects of human interference with the natural cycle of carbon by burning fossil fuels, harvesting forests, and converting land to agriculture are reflected most clearly by the phenomenon of increasing concentration of atmospheric CO_2. If current trends continue, the atmospheric concentration will exceed 600 parts per million by volume (ppmv) by the year 2040—more than two times the pre-industrial level. The increase in CO_2 is important because, in contrast to atmospheric O_2 and N_2, CO_2 absorbs infrared radiation emitted by the Earth and prevents the escape of some of the normally outgoing radiation. This is now popularly known as the "greenhouse" effect.

The present concentration of CO_2 in the atmosphere is 338 ppmv or, in terms of mass of carbon (C), 728 x 10^{15} g C. Within one year, seasonal differences in photosynthesis and respiration within the biosphere create an oscillation in the atmospheric CO_2 concentration, with an amplitude of roughly 5 ppmv or 10.6 x 10^{15} g C y^{-1}. Attempts have been made to detect changes in the amplitude of this oscillation as a way to infer changes in the size of biospheric pools of carbon, but the results have been inconclusive.

Estimates of the amount of carbon in living organic matter on land vary between (450-900) x 10^{15} g C, and although soil organic matter (humus) is a major active reservoir in the global carbon cycle, there are few data on its size and activity. Estimates range from (700-1800) x 10^{15} g C. Estimates of total primary production, respiration and detrital decay rates also vary greatly. There are two principal reasons for this uncertainty: (1) the method of scaling from selected local sites of measurement to biome-wide estimates is not rigorous, and (2) uncertainties exist about the geographic extent of different biomes.

Although knowledge of the carbon cycle is a key to comprehending the biosphere, it is not well understood. Uncertainty centers partly on the role of terrestrial biomes, in which at least two factors govern the level of carbon storage. First and most obvious is the alteration of the Earth's surface, such as the conversion of forest to agriculture which often results in a net release of CO_2 to the atmosphere. Second and more subtle is the possible change in net ecosystem production, and hence carbon storage, resulting from changes in other global cycles. For instance, the burning of fossil fuels not only releases large amounts of carbon to the atmosphere, it also increases the input of nitrogen and sulfur. Some fraction of these compounds must enter forest biomes. Will this fertilization of forests stimulate both the fixation and storage of carbon?

Clarification of the first factor by the measurement of extent and change in area is obtained readily from analysis of satellite imagery. With regard to the second, however, measuring the amount of biomass per unit area in a given system, the annual dynamics of this biomass, the change in this biomass following disturbance, and the flux of trace gases, carbon, and essential nutrients in both disturbed and undisturbed terrestrial biomes will require advances in remote sensing and extensive *in situ* studies.

Direct calculations of net carbon released from the biosphere have accounted for various estimates of disturbances and the uncertainties of biotic response. They conclude that from 1860 to 1980 the mean release totaled 150 x 10^{15} g C, with a current annual release between (1-3) x 10^{15} g C y^{-1}. However, without far more refined information about disturbance rates and ecosystem responses, it will be impossible to appraise with confidence the role of the biosphere in the global carbon cycle.

Uncertainties in our understanding of the carbon cycle lead to serious difficulties in balancing the current budget of atmospheric CO_2. Simply stated, the annual budget equation

Input into atmosphere

Fossil Fuel:	5 x 10^{15} g C y^{-1}
Deforestation-Regrowth:	2 x 10^{15} g C y^{-1}
	7 x 10^{15} g C y^{-1}

Uptake

Atmospheric Increase:	2.5 x 10^{15} g C y^{-1}
Oceanic Uptake:	2.5 x 10^{15} g C y^{-1}
Fertilization Effects:	?
	5 x 10^{15} g C y^{-1}

does not balance unless:

1. Fertilization effects, either terrestrial or aquatic, equal deforestation-regrowth.
2. The problem vanishes (i.e., deforestation equals regrowth).
3. The oceanic uptake is grossly underestimated.

There are a number of questions which must be addressed. What are the extent and carbon content of major terrestrial biomes? What is the response of terrestrial biomes to human perturbations? What factors control the internal routes for uptake and release of carbon? What are the key processes which control the exchange of carbon between the atmosphere and ocean?

Returning to the issue of land use, the harvesting of forests and the creation and managing of agricultural land often results in the loss of nitrogen to the atmosphere and adjacent aquatic ecosystem. First, nitrogen leaves the forests in harvested material. Second, erosion, accelerated by the harvest, carries off nitrogen-bearing soil. Third, forest cutting can dramatically raise losses of inorganic nitrogen, principally nitrate removed in solution by streams that drain cutover areas. A fourth pathway may also exist: wood harvests may stimulate denitrification.

Further understanding of either the carbon or the nitrogen cycle will require a clearer picture of the coupling between the two elements. Do such losses of nitrogen following forest harvest reduce the carbon storage capacity for the system? What are the magnitudes of nutrient inputs to aquatic systems when adjacent terrestrial biomes are disturbed? What are the consequences of these inputs? For example, will river eutrophication increase carbon storage? Will it increase N_2O fluxes to the atmosphere?

There are three characteristic dynamics in the nitrogen cycle: long-term dynamics involving the flux of N_2 to and from the atmosphere; a far more rapid baseline flux of nitrogen within the biosphere; and an increasing flux of nitrogen throughout the system associated with human activity.

Humans are now, significantly modifying the nitrogen cycle. High temperature combustion adds 20×10^{12} g N y^{-1} to the atmosphere, and this nitrogen could have an important impact on atmospheric chemistry, biological productivity, and precipitation chemistry. In addition, modern agriculture has increased the rate of decomposition of organic matter in the soil and thus the return of N_2 to the atmosphere. On the other hand, the introduction of monocultures with legumes that can fix N_2 through symbiosis with certain bacteria probably implies a net increased fixation. In addition, approximately 40×10^{12} g N y^{-1} of fixed nitrogen is added to the terrestrial system annually as fertilizer.

Still, the amount of nitrogen fixed by man annually is small compared with the existing pools in the soil and in the oceans. These pools will therefore be influenced only slowly. It will take several decades, maybe a century or more, before significant global changes may be expected due to man's activities, except locally in particular soil and water systems. But for the very reasons that it would be several decades before any significant global changes could be apparent, these same reasons imply that it would take a long time for conditions to return to an earlier balance once a change has begun to occur.

In this context, then, there are a number of important open questions about the nitrogen cycle. What is the magnitude of the nitrogen fixation rate in major biomes? How much of this fixation is under control of humans, and how is the fixation rate changing? Are anthropogenic disturbances of the nitrogen cycle causing a decline in the fertility and productivity of major terrestrial biomes? Are stores of nitrogen in major soil systems deteriorating? What effect does anthropogenic N have on rivers and coastal biomes? Is sewage N damaging or enhancing marine biotic resources? Have NO_x and N_2O emissions from combustion and agricultural soils enhanced global concentrations of these gases? If so, what effects may be expected on other important species, such as ozone?

Phosphorus is essential to plant growth and yet is available in far smaller amounts than carbon and nitrogen in the biosphere. Its relative insolubility limits its availability to organisms in soils, rivers, and oceans, and sedimentary deposits provide its major reservoirs. In the absence of human activity, these characteristics limit this element's role in global biogeochemical cycling. Human activity, however, has altered the availability of phosphorus in direct and indirect ways. The application of phosphorus fertilizer is a direct perturbation, but subtler alterations of the phosphorus cycle may influence the dynamics of other cycles. Fire, either natural or as a management technique, may increase the available stocks of phosphorus, since oxidation of plant litter transforms organically bound phosphorus into more available forms. Increased levels of available phosphorus can, in turn, raise the rate of nitrogen mineralization in soils. In addition, there is a possible coupling between C and N through fire. Rapid oxidation of the carbon in litter with a high C:N ratio reduces the amount of nitrogen that can be immobilized by microorganisms during decay, thereby increasing the amount of N available to plants.

Atmospheric transfer processes are unimportant for phosphorus, in contrast to carbon, nitrogen, and sulfur. Rather, the major phosphorus exchanges are associated with dissolved and particulate transport in rivers and with weathering processes and diagenesis in soils and sediments. Much of the phosphorus is biologically unavailable while in the rivers, and there are major questions about the fraction of river-borne phosphorus which participates in the biological cycle and the time scale for effective transfer to the ocean. The level of available phosphorus increases dramatically in the mixing zone between fresh river water and ocean waters. Most of this increase is a result of desorption or dissolution of riverine phosphorus. However, it may partly arise from marine sources, and much work remains to be done to resolve the question. Biological uptake of phosphorus in the photic zone of the ocean is extremely rapid, and surface waters are typically devoid of mineral phosphorus. It appears that PO_4^{-3} may be kinetically controlled by biological processes in the sea, but the basic mechanisms remain controversial. Additional uncertainty is associated with storage of phosphorus in estuarine and coastal sediments. This issue is important since this phosphorus may be mobilized during low stand of sea level (e.g., during glaciation) thereby potentially increasing marine biological activity.

Major questions concerning the phosphorus cycle on global scales may be summarized as follows: What are the mechanisms controlling availability of phosphorus in terrestrial soils, and how does phosphorus availability respond to anthropogenic perturbations (e.g., acid deposition)? What is the magnitude of the river-borne flux of phosphorus to the ocean? How is the chemical availability of this phosphorus controlled? Is productivity of the surface ocean limited by phosphorus? For example, would biological fixation of nitrogen increase dramatically in coastal areas in response to anthropogenic enhancement of river-borne phosphorus?

Sulfur plays an equally important role in maintaining biological systems, since it is an essential nutrient for all plants, bacteria, and animals. In fact, sulfur is a limiting nutrient in parts of Canada's grain belt. Additionally, because it is so widely available in seawater, it has great impact on the cycles of carbon and energy in marine ecosystems. Reduced sulfur gases are emitted primarily as the result of biological processes in ocean surface water and in salt and fresh water marshes. Sulfur-reducing bacteria gain energy by oxidizing organic carbon to CO_2 using sulfate, which is coverted to H_2S or to sulfur compounds of intermediate oxidation states. These compounds may be oxidized by sulfur-oxidizing bacteria or may be emitted to the atmosphere. Several measurements have been made of the fluxes of H_2S, $(CH_3)_2S$, CS_2, and COS in various locations (salt and fresh-water marshes in particular), but more needs to be done to define the biological sources of reduced sulfur gases and the extent to which they have been perturbed by anthropogenic activity.

On a global scale, the sulfur cycle is assuming increasing importance as the impact of acid rain and atmospheric sulfur pollution become known. Indirect calculations suggests that emissions of gaseous sulfur to the atmosphere from fossil fuel combustion are already on the same order of magnitude as discharges from natural systems. In comparison, man's contributions to the global cycles of carbon, nitrogen, and phosphorus represent relatively minor components of their respective natural fluxes, although, as noted earlier, human activity is altering these cycles in potentially important ways.

The following questions regarding the sulfur cycle need to be addressed: What are the magnitudes of the biological fluxes of reduced sulfur gases? What processes contol these magnitudes and how have they been perturbed by human activity? What is the fate of industrially released SO_2 and how does it affect the areas in which it is deposited? What controls the transformations of sulfur gases in the atmosphere? Are there substantial anthropogenic perturbations of the concentrations of long-lived gases such as COS and CS_2.

To improve our knowledge of these cycles and their interaction, we need additional information on biotic control systems as expressed in elemental interactions, as well as better estimates of the rates of various disturbances and the size of natural fluxes. Further, it is vital that we combine current and new information in a way that allows testing of various hypotheses about the workings of global biogeochemical systems. This will enable us both to assess our current knowledge and to evaluate the gaps in it.

The dynamic biogeochemical equilibria among the major pools of carbon, nitrogen, sulfur, and phosphorus represented by terrestrial biomes, the world's ocean, and the troposphere have been disturbed, and hence the interlocking systems are now in transition. Since even the most rapid processes of adjustment among the reservoirs take decades, new equilibria are far from being established. In a sense, therefore, these human-induced perturbations and the system's subsequent responses constitute an on-going biogeochemical experiment at the global level. Consequently, if we ask the right questions and if we collect the appropriate data of sufficient accuracy and in a timely fashion, then perhaps this experiment will give us major new insights into the basic processes.

BIOGEOCHEMICAL CONSIDERATIONS

C. C. Delwiche

SCIENTIFIC OBJECTIVES FOR THE 1990s

Some questions relating to biogeochemical cycles and the nature of the biosphere driving them can best be approached by means of remote (satellite) monitoring. Important among these are the distribution of various ecosystems and the boundaries between them, the extent and rate of modification of ecosystems by human or other factors, and various climatic and physical factors affecting ecosystem performance as influenced by human or natural processes.

An important concern of the biologist or geobiologist with the biogeochemical cycles that involve atmospheric constituents, is that many of these cycles have been altered by a factor of two or more from their "natural" states since human population has become large enough to have a direct and visible effect on them. Although developing over ten thousand years or more, this human influence has become most noticeable since the beginning of the industrial revolution, and most noticed within the past two or three decades.

Because of the potential large effect these human alterations of biogeochemical cycles may have on the habitability of the globe and the survival of its biota, missing information should be obtained promptly in order to aid in guiding public policy.

Remote sensing techniques are not a complete solution to the problem of gathering this information, but they can help in obtaining some of it, and in some cases, probably are the best means.

Atmospheric concentration of various gases of biological or industrial origin such as carbon dioxide, carbon monoxide, nitrous oxide, other oxides of nitrogen, ammonia and compounds of sulfur are amoung the commonly cited gaseous compounds which should be monitored. The absolute concentration of these constituents on a long-term basis and with the best possible accuracy can be determined either by ground based stations or possibly by remote means, but source strengths and their distribution on the globe probably are best determined remotely.

Erosion of soil is perhaps one of the more significant processes by which natural cycles have been altered. Not only does this represent the loss of a valuable and fragile resource, but the processes of erosion also result in the alteration of properties of rivers and estuaries, in eutrophication of waters and probably even the fertilization of ocean waters that have previously been low in productivity. The consequences of such alteration are difficult to evaluate and are clearly in need of study. The monitoring of river plumes as an indicator of erosion and of other waters as an indicator of eutrophication is an appropriate mission for remote sensing instruments.

Volatilization of heavy metals, either as their methylated derivatives or as the metal itself (e.g., mercury) beyond historical rates as the result of human activities has greatly altered the cycles of some of these metals, again with unknown consquences and to an unknown extent. Instrumentation to detect and monitor the concentration of these volatiles in the atmosphere and their sources and sinks would be desirable. It would have to be capable of detecting exceedingly low concentrations, and present instrumentation may not have the necessary sensitivity for remote determination, but if it can be developed, it would be highly desirable.

Natural emissions of non-methane hydrocarbons and other organics by higher plants is known to occur, but we lack the information to interpret the significance of these natural processes relative to human sources of similar compounds. These also are low in concentration.

Surface (soil and water) hydrogen ion concentration is a most fundamental property which if measured accurately and followed with time would enable the interpretation of many processes known or suspected to have potentially damaging effects. There is no routine means by which such measurement can be accomplished now, but such a means should be possible and deserves attention.

Boundaries between ecosystems are the most sensitive integrators of changing conditions. These can be observed by direct (visible) photographic means. Existing images contain some of this information and systematic interpretation will provide information a decade or more old. Monitoring by Landsat or equivalent imaging techniques should be continued. Some more specific boundary areas should be examined with higher resolution.

Chlorophyll content of surface waters is an indicator of primary production in continental and marine systems. Refinement of methods for monitoring chlorophyll content and routine application of the method to detect change is indicated.

Erosion, desertification, deforestation and various other physical processes of both natural and human origin alter these biogeochemical cycles significantly. The evaluation of this change deserves immediate attention.

Listed in Table A2 are some atmospheric components of biogeochemical origin together with their concentration range and other information. Nitrogen and oxygen, both also of biological origin, are not listed because no significant change in their concentration is indicated. Atmospheric nitrogen concentration has not been affected by human activity to any measurable extent and any changes which may have occurred in total atmospheric nitrogen by this means probably would not affect the biota significantly. Changes in oxygen concentration would be of great interest but present analytical techniques probably are not precise enough to determine any likely change to date, particularly by remote means.

TABLE A2. Atmospheric Constituents of Biogeochemical Origin, Their Fractional Abundance, Residence Time and (Probable) Spatial or Short-Term Variability

Compound	Mixing ratio range	Residence time range	Remarks
CO_2	10^{-3}-10^{-4}	Decade	Both annual and trend information needed
CO	10^{-5}-10^{-7}	Days	Point and area sources profiles desirable
N_2O	10^{-6}-10^{-7}	½ Decade	Point and area sources profiles desirable
CH_4	10^{-5}-10^{-6}	Years	Point and area sources profiles desirable
DMS	10^{-5}-10^{-7}	Hours	Estuarial and other anoxic areas
H_2S	10^{-6}-10^{-7}	Hours	Estuarial and other anoxic areas
NH_3	10^{-5}-10^{-7}	Hours	Point and area sources
CH_3Hg	$<10^{-7}$	?	Vegetation and anoxic areas

For many of these atmospheric constituents, concentration profiles near the Earth surface in some locations are particularly desirable. Present instrument capabilities suggest that LIDAR would be the most likely device, and even this would need refinement beyond present capabilities. Vertical resolution to 10 meters or better with low detection limits is desirable.

OBSERVATIONAL REQUIREMENTS

Listed below are specific observations that should be both obtainable and desirable in the 1990s, together with abbreviated comments concerning justification or methodology as appropriate. Table A3 summarizes measurements, providing suggested timing of measurement, possible vehicles or techniques, special needs and limitations.

Nitrous Oxide: Concentration profiles both in stratosphere and troposphere are desirable. Gradients near the Earth surface, both over oceans and selected soil sources are desirable. Because of long residence times in the atmosphere (and implied weak source strength), these latter measurements may not be possible by remote means with expected precision.

Reduced Sulfur: These compounds (particularly DMS and H_2S) probably are produced in larger quantities than normally is thought because natural processes may have been underestimated. Specific sites such as the oceans and continental shelf and estuary waters as well as some of the continental margins are sources that need study. Whether concentrations are high enough to permit remote assay (in 1990) is not certain.

Carbon Monoxide: Ocean surface source strengths and some land sources and sinks probably can be obtained by remote means. Flux rates and long-term trends in atmospheric CO levels are needed in order that the human contribution be placed in proper context.

Mercury and Methyl Mercury: Identification of sources and relative quantities of each, from waters, soil and vegetation, in comparison with industrial sources is needed. Other metals, on aerosols such as organio-metals from vegetation sources are suspected. Their source strengths relative to industrial sources of mercury is unknown. Concentrations are low relative to detection capabilities.

Soil Surface pH: Desirable but probably not possible by remote means (other than by inference from vegetable and other variables). This would make possible interpretation of biological processes and human changes.

Ecosystem Boundaries: As sensitive indicators of other change. Examples: tundra-taiga, taiga-marsh, prairie-forest, desert-steppe, etc.

River Plumes: As an indicator of erosion and eutrophication as well as tracers of ocean currents near shore, the course of a river changes with time as well as the influence of human activity.

Methane and Other Hydrocarbons of Biological Origin: Determination of sources and their changes with time will assist in sorting out the biological and other contributions of these organics. Long-term trends and fluctuations are still uncertain.

Ocean Chlorophyll: As an indicator of net primary production in the ocean and its changes with time (possibly as the result of mineral contributions from erosion and other sources), ocean chlorophyll should be a good presumptive indicator of change.

Other: As more sensitive and more precise techniques become available, and as other needs are recognized, this list undoubtedly will expand. The data which these estimates will provide, coupled with other information obtainable only by direct on-site means, will make possible a more accurate understanding of the processes involved which, in turn, will dictate need for other information.

TABLE A3. Observation Requirements: Biogeochemical Sources, Sinks and Fluxes

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Ecosystem boundaries	As indicators of change due to altered environment	Visible or near IR
River plumes	Erosion and eutrophication	Visible or near IR
Ocean chlorophyll	Indicator of primary production and change in production	Visible or lidar, fluorescence
	Atmospheric Parameters	
CH_4—Total tropospheric column content CH_4—Source strength (gradient) over selected areas	Biological and human source strengths and residence time	IR or lidar absorption Low concentration may limit determination
N_2O Total atmospheric—gradients (if possible) over specific sources	Biological and human (agricultural) sources	IR or lidar absorption Low concentration may limit determination
CH_3Br Total atmospheric gradients over specified areas (if possible)	Identification of suspected biological sources	Absorption—probably lidar
$(CH_3)_2S$, (CH_3) SH, SH_2 Total atmospheric gradients over specified areas	Identification of suspected biological sources (and times)	Absorption (IR or lidar) Low concentration may limit determination
NH_3 Tropospheric gradient over specified areas (forests, anoxic areas, point sources)	Biological source strengths	?
Non-methane hydrocarbons Tropospheric gradients over specified areas	Identification of biological source strengths (and times)	?

Note: Time schedules for all of these are variable. Both diurnal and seasonal variability are anticipated.

BIOLOGICAL OCEANOGRAPHY

Mark R. Abbott

SCIENTIFIC OBJECTIVES FOR THE 1990s

The world ocean is extremely important in the global cycling of nutrients and in the productivity of the biosphere. Within biogeochemical cycling, the ocean behaves as a large reservoir of these nutrients. Exchange of materials between deep and surface waters, between land and ocean, and between air and ocean are crucial links in this system. These exchange rates are, in many cases, not very well known. Ocean productivity, while small on a per area basis, is a large fraction of total biosphere production because of the ocean's large area. Such productivity is closely associated with biogeochemical cycling. For example, the transformation rate of nitrate into organic nitrogen compounds depends in part on phytoplankton productivity. In turn, productivity is also affected by the availability of various nutrients. Thus, while some of the transformations and distributions of these nutrients are related to physical and geochemical processes, the influence of biological processes cannot be overlooked. The ocean is one component of the biosphere system in which the transformations of materials and the transfer of energy form the basis of all interactions.

Although the study of biogeochemical cycles and energy transfer are central to most studies in biological oceanography, the possibility and importance of global studies has only been recently recognized, from both a scientific and a pragmatic standpoint. For example, variations within the global carbon cycle may have significant effects on climate. Changes in supply rates of nutrients or pollutants to coastal waters may affect distant fisheries. Variations in ocean climate in the eastern tropical Pacific may influence the productivity of coastal waters off California. The perception of the world as a global ecosystem implies that local changes may have global consequences. The development of a global observation system is imperative to monitor and predict these changes.

Within the framework of global biogeochemical cycles and ocean productivity, there are two areas that will be of particular interest to biological oceanography in the 1990s. The first is the mapping in space and time of the biomass and productivity of phytoplankton in the world ocean. The second area is the coupling of biological and physical processes as it affects the distribution and growth rate of phytoplankton biomass. Certainly other areas will be of interest to biological oceanographers, but these two areas are amenable to observations from satellites.

Temporal and spatial variability is a regular feature of marine ecosystems. Heterogeneity in distributions and growth rates occurs at all scales, from seconds to decades (and longer) and from millimeters to thousands of kilometers. Such variability not only affects the cycling of materials at the level of the primary producers (phytoplankton), but it also affects the transfer of materials and energy up the food chain. This is caused in part by the different characteristic time and length scales associated with each trophic level. For example, phytoplankton typically reproduce every few days and may only move a few tens of kilometers in that period; zooplankton typically reproduce every 100 days and may move several hundred kilometers in that period. Thus, studies of productivity will require proper observation and understanding of this variability.

The causes of biological heterogeneity are in large part a result of fluctuations in the physical processes of the ocean. As phytoplankton are largely at the mercy of water motions, their vertical and horizontal distributions will be generally determined by the constant movement of the ocean. These motions will not only affect distribution directly by determining positions but also indirectly by influencing nutrient and light supply rates. It is the variability of these processes which results in biological fluctuations. Therefore, studies of ocean productivity must be concerned with the physical dynamics as well as biological processes.

The temporal and spatial distributions of productivity and biomass at mesoscales (2-20 days, 10-200 km) and large scales (>1 month, >500 km) are particularly difficult to sample with traditional means (a few slow-moving ships). However, the intense variability of mesoscale features and their overlap with the characteristic time and space scales of phytoplankton make them particularly important to ocean productivity. Mappings of large-scale distributions are important for the development of a global "climatology" of productivity and biomass to use in studies of global biogeochemical studies, and for the study of global changes in ocean productivity and their relationship to large-scale changes in the atmosphere. For example, key questions in this area are: 1) Where are regions of high mesoscale variability? 2) How does mesoscale variability affect global productivity and biogeochemical cycling? 3) What is the global "climatology" of productivity and biomass and how does it vary seasonally and interannually? 4) What are the differences and similarities between the northern and southern oceans and between coastal and oceanic water? 5) What is the vertical structure of biomass and productivity? 6) How does vertical structure affect horizontal processes? and 7) What is the temporal pattern of vertical structure?

Although these measurements are phrased in terms of biomass and productivity, additional variables will also be of interest. Biomass can be refined into smaller categories, for example phytoplankton pigment groups that are more ecologically meaningful. That is, the flow of energy and transformations of nutrients depend strongly on the type of primary producers present in an ecosystem. For example, phytoplankton differ in their palatibility to zooplankton and in their nutrient requirements. Thus, more refined measurements of phytoplankton biomass and productivity will be required. Another measurement of biomass that may be useful is bioluminescence. Although bioluminescence is not restricted to phytoplankton, it is related to physical and biological processes. As little is known of its global distribution, measurements of bioluminescence will help in understanding its causes and its relationship to particular organism groups (e.g., dinoflagellates).

To understand this observed temporal and spatial variability requires measurements of physical processes and knowledge of their coupling to biological processes. Key questions concerning the role of physical forcing are: (1) What is the relationship of mesoscale phenomena (eddies, meandering fronts, coastal jets, etc.) to mesoscale distributions of biomass and productivity? (2) What are the effects of topography (both bottom and coastal topography such as headlands) on biological processes? (3) What is the connection between mesoscale and large-scale processes? (4) What processes control the exchange of materials between coastal and oceanic waters? (5) How does the general circulation of the ocean (including surface currents, under-currents, and long waves) influence distant geographic areas of the world ocean? (6) How does the atmospheric climate affect biological processes? (7) What is the distribution of major nutrients? (8) Can we estimate supply rates of nutrients from the deep ocean to the upper waters? and (9) Can we parameterize vertical mixing rates of the surface layer?

The key scientific issues for biological oceanography in the 1990s are issues that have been recognized for decades. The difference is that the tools for addressing these issues are now becoming available. We have proposed a framework whereby the issues of biogeochemical cycling and ocean poductivity are investigated in terms of observed mesoscale and larger (including global) scale temporal and spatial variability and in terms of coupled biological and physical processes.

OBSERVATIONAL REQUIREMENTS

With the role of primary production in global biogeochemical cycles as the framework for investigations in biological oceanography, there are two problems to be addressed. The first problem is to characterize the temporal and spatial variability of phytoplankton biomass and productivity which is ubiquitous at all time and space scales in the ocean. The dominance of physical processes in the creation of this variability leads to the second problem; it is necessary to understand the coupling of biological and physical processes. Remote sensing from satellites can address these problems with global observations of mesoscale (2-20 days, 10-200 km) features over a long period of time.

Mapping of near-surface photoplankton biomass could be done by an Ocean Color Imager (MAREX Report, Ocean Color Science Working Group 1982). The detailed optical and orbital requirements are described in this report. In summary, a sun-synchronous (equator crossing at near local solar noon) orbit providing daily global coverage is required. Spatial resolution should be <1.0 km in the coastal ocean, and 4 km x 4 km in the open ocean. Adequate visible and near IR bands to detect the color shift from blue to green with increasing chlorophyll concentration and to remove atmospheric effects (Rayleigh and aerosol scattering) are required. A tiltable mirror is also necessary to avoid sunglint.

A more sophisticated instrument could continue these near-surface biomass measurements while providing more detailed spectral information in order to determine the composition of the phytoplankton biomass and to support more sophisticated routines to remove atmospheric and water turbidity effects. As phytoplankton groups vary in their pigment composition, their effect on ocean color will also vary. Orbit and sampling characteristics would be the same as the Ocean Color Imager. The instrument itself would be sensitive to wave-lengths between 350 nm and 800 nm with a 10 nm resoluton. Such information should help separate a broad category such as biomass into smaller and more ecologically meaningful groups. Also, a broader range of water and atmospheric types could be investigated.

Observation of chlorophyll *a* fluorescence when compared with chlorophyll *a* measurements may be a useful indicator of the health and productivity of the phytoplankton. Fluorescence measurements must be made simultaneously with the chlorophyll measurements and would therefore have the same orbit and sampling characteristics as described. The instrument should have a 5 nm resolution from 600 to 750 nm. This range covers the broad fluorescence line centered at 685 nm. As other pigments fluoresce at other wavelengths, future sensors may be centered around additional wavelengths.

The mapping of the global distribution of bioluminescence in the ocean is another requirement. Such measurements must be made during moonless nights. A spatial resolution of 5 km x 5 km and global sampling of once per month would be adequate for an initial map. The sensor should have a band resoluton of 10 nm from 450 to 550 nm.

As satellite sensors can only measure biological processes near the ocean surface, the capability to transmit and receive information from *in situ* sensors via satellite is also a requirement. Such sensors would measure both distributions and vertical exchange processes occurring at depth. These sensors could be both moored or freely drifting so accurate location by satellite is also necessary.

The second problem of understanding the coupling of biological and physical processes requires physical observations as well as the biological observations described above. Detailed measurement and orbit requirements can be found in the physical oceanography section and in working group reports cited therein.

Some observations are of particular interest in biological oceanography. Observations of sea surface topography will address the issue of the time variation of ocean circulation. Such information, when coupled with wind stress measurements, will improve our understanding of ocean-atmosphere interactions and the role of large-scale phenomena such as long waves in creating interactions between distant areas of the ocean. Measurement of mesoscale features (e.g., sea surface temperature) can be used to develop a "climatology" of the mesoscale eddy field and explore processes such as topographic effects or cross-shelf transport of materials. Information on wind stress would also be required to understand forcing of the eddy field. Observations of the oceanic heat and momentum budgets would also be useful in studying air-sea interaction and vertical mixing rates. A range of measurements would be necessary such as wind stress, air-sea temperature difference, humidity near the sea surface, radiative flux, and mixed layer depth. (See Guidelines for the Air-Sea Interaction Special Study, JPL/SIO Workshop Report 1980 for detailed requirements.)

It is necessary to emphasize that physical measurements are essential for the understanding of biological processes in the ocean. Although not all of these measurements need to be exactly coincident with the biological measurements, the mesoscale feature measurements (in particular sea surface temperature) should be done at the same time as the biomass and fluorescence measurements. Other measurements could be made at 2-10 day intervals, depending on physical oceanography requirements.

The major observational parameters for biological oceanography in the 1990s are summarized in Table A4.

TABLE A4. Observation Requirements: Biological Oceanography

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Near-surface phytoplankton biomass	Mapping of variability	Ocean color (see MAREX report). Sun-synchronous orbit; global coverage (daily) 1 km resolution coastal ocean, 4 km × 4 km open ocean, adequate bands to detect blue shift.
Phytoplankton pigment groups	Mapping of biomass; also separation of biomass into more ecologically meaningful groups	Detailed spectral data; 10 nm resolution, 400-800 nm band; 1 km resolution coastal ocean, 4 km × 4 km open ocean, global coverage.
Fluorescence at 685 nm	Estimate productivity from fluorescence/chlorophyll	5 nm resolution near 685 nm. Additional bands for atmospheric correction.
Bioluminescence	Initial mapping on global scales; begin characterization of patterns	Nighttime measurement; moonless night; blue-green wavelength (~500 nm, 5-10 nm resolution); global coverage.
Subsurface biomass, productivity, physical processes	Characterize processes below effective sampling depth of satellite, vertical mixing rates of surface layer; exchanges between surface and deep water; tracking of mesoscale features	*In situ* measurements with satellite relay; pulsed fluorescence for productivity, biomass, current meters, thermistors, drifting and moored systems.
Sea surface topography/sea surface stress	Time variation of the general circulation of the ocean; propagation of long waves; coupling with atmosphere; "teleconnections" between distant areas of the ocean	See phys. oceanogr. requirements TOPEX working group, scatterometer working group. Long time series.
Mesoscale feature tracking and detection	Coupling of mesoscale and large-scale features; topographic effects; "climatology" of eddy field, cross-shelf transport of materials	1 km resolution, global coverage, daily coverage. Can use sea surface temperature, topography, ocean color, SAR.
Heat and momentum budgets	Vertical mixing rates; air-sea interactions	Air-sea temperature difference wind stress; net surface radiation; see Air-sea interaction report, JPL.

INLAND AQUATIC RESOURCES AND BIOGEOCHEMICAL CYCLES

John M. Melack

SCIENTIFIC OBJECTIVES FOR THE 1990s

The biosphere is the entire planetary system that includes, sustains and is influenced by life. The central issue of the science of the biosphere is the extent to which the Earth's surface, atmosphere and hydrosphere is the result of biological rather than abiotic processes. Space science and technology can accelerate our understanding of global biological processes by providing repetitive synoptic observations on large spatial scales once the relationships between the processes and the remotely sensed quantities are established. Especially promising applications of space technology are the measurement of biological productivity and portions of geochemical cycles in aquatic ecosystems and the evaluation and management of the quality of freshwater resources.

The rates at which critical chemical elements such as nitrogen or phosphorus must be cycled in order to sustain life are far more rapid than most geologic processes. Yet, the extent to which organisms can control the exchange of gases with the atmosphere, solutes with the hydrosphere and particulates with the atmosphere, hydrosphere and sediments is an open question. That organisms can have effects out of proportion to their mass or relative abundance is known. For example, diatoms are now major agents in the flux of carbon from the atmosphere to the sediments in lakes and oceans; this flux may help reduce the elevation of atmospheric CO_2 derived from fossil fuel combustion and deforestation. Another important example is the wetlands that fringe rivers, lakes and continental margins. Biological processes in these anaerobic environments which are rich in organic matter may be major sources of reduced gases such as methane, H_2S and nitrogen. In turn, alterations in the efflux of methane can change the Earth's surface temperature. To determine the quantitative role of diatoms or wetlands in global biogeochemical cycles requires (1) estimates of the abundance or areal extent of these organisms or ecosystems and (2) measurements of the fixation of carbon, sedimentation rates and generation of gases. To satisfy these requirements entails measurements on large spatial scales (thousands of square kilometers) but on short time scales (hours to weeks).

Much of the motivation to study the biosphere has come from concerns over the impact of industrial civilization on the biosphere and human welfare. Special issues with considerable research effort in progress are the worldwide dispersion of chemical toxins such as DDT and radionuclides, eutrophication of water supplies, deforestation and desertification, acid rain and global increases in atmospheric CO_2. Understanding of these processes on a global scale requires non-steady state models that include oceanic and atmospheric circulation and allow spatial and temporal variation. Clearly, geophysical research must be blended with biological research to develop a science of the biosphere.

Inland Aquatic Resources And Biochemical Cycles

Without adequate supplies of unpolluted freshwater, society as we know would not exist. Indeed, freshwater could well become a primary factor limiting the world economic development in the next century. The management of freshwater is now based on empirical relations between forcing functions such as inputs of nutrients, sediments, heat or toxins and the observed responses of biological communities such as algal biomass or fish yields. These statistical models are largely based on short-term studies in north temperate lakes and have very wide confidence bounds even for these lakes. Extrapolation of these models outside the temperate zone is pure guesswork. Yet, vast areas of freshwater comprising diverse natural ecosystems and economically important water bodies are in tropical and subtropical regions.

Plants are at the base of all food webs and sustain natural ecosystems and mankind. The fixation of carbon dioxide and formation of high energy chemical intermediates by plants is called primary productivity. Besides the obvious link to the carbon cycle, the production of new plant material requires many other elements such as nitrogen, phosphorus, sulfur and a variety of metals.

Compilations of world-wide estimates of aquatic primary productivity are judged to be underestimated by a factor of 2-10 and lack rigorously derived confidence bounds. Technical difficulties with the measurements of carbon fixation and insufficient sampling of the considerable spatial and temporal variability leads to this unsatisfactory state. Less certain is the fate of the fixed carbon; how much is sedimented, consumed by plankton and fishes, exported or recycled? Furthermore, even less understood are the complex linkages between the nitrogen, phosphorus, etc., cycles and that of carbon.

In light of the large scale modification of the carbon, nitrogen, sulfur and phosphorus cycles by man's activities, an acute need exists to devote a major effort to measurement of the natural and total fluxes of these elements on a planetary scale. For example, during the last century, man's ability to extract nitrogen from the atmosphere has come to rival that of N_2 fixation by bacteria. Nitrogen loadings from agrarian runoff, deforestation and urban sewage have already impacted local streams, some large lakes and major rivers.

Wetlands fringe many lakes and continents and form in floodplains along many rivers. Although minute in area compared to land or oceans, wetlands have significant biogeochemical roles on a global scale: (1) Wetlands are among the most productive ecosystems on earth and export considerable animal protein. (2) Wetlands are loci for anaerobic, microbial activity and can strongly influence the fluxes of CH_4, H_2S, N_2, NH_4 and CO_2 to the atmosphere. (3) Wetlands function much as biological filters between land and open water. Intense biological activities occur in them; amplification up the food chain of the concentration of toxins is known to occur and nutrient loading to the neighboring waters is known to be influenced. (4) Long-term storage of organic carbon occurs in wetlands as illustrated by immense deposits of peat and some oil fields. Much of the material summarized above is derived from a strategy document, *Towards a Science of the Biosphere*, prepared by the Committee on Planetary Biology for the Space Science Board.

OBSERVATIONAL REQUIREMENTS

Inland waters have several distinctive characteristics which require special attention:

1. Sizes are moderate to small (e.g., 100 km to < 1 km in length)
2. Basins are dispersed over large areas of land
3. Long spatial interfaces between land and water occur
4. A very wide range of optical conditions are caused by large differences in the kind and abundance of suspended particles, e.g. chlorophyll concentrations range from 0.01 to 1000 mg/m^3
5. Rapid changes in biological, chemical and physical conditions are usual. Time scales of these changes range from seconds to weeks but ecologically important changes are usually on scales of days
6. Episodic events and periodic fluctuations are important
7. Strong horizontal and vertical gradients in biological and physicochemical conditions are typical

To observe such ecosystems requires high resolution (e.g., 30 m), multispectral (e.g., optical, microwave) imaging systems with frequent repeat coverage. The principal observational requirements for inland waters are summarized in Table A5.

The two, major scientific problems amenable to remote sensing are measurements of biological productivity and of the fluxes between inland waters and oceans, land and the atmosphere. Biological productivity should be examined mainly in wetlands and lakes. Fluxes to the oceans are largely via rivers, while exchanges with the atmosphere are important in rivers, lakes and wetlands. Land use in the drainage basins and hydrological conditions determine the fluxes from land to inland waters.

Biological productivity is generally estimated from measurements of photosynthetic activity. Such estimates require measurements of the quantity of photosynthesizing material, the rate of carbon fixation and the proportion of fixed carbon that is consumable by other organisms or storeable in sediments. The nutritive and biogeochemical significance of the organic matter is also dependent upon the content of other elements such as nitrogen, phosphorus and sulfur.

Imagery from space can greatly improve measurements of the abundance and spatial distribution of photosynthesizing material. Current satellite-borne sensors have demonstrated some potential in chlorophyll detection but significant improvements are necessary. The Coastal Zone Color Scanner on the Nimbus 7 Satellite is specifically designed for sensing chlorophyll in clear water, but it has coarse spatial resolution (0.8 km), limited global coverage and lacks adequate spectral resolution to cope with high chlorophyll levels and turbid water. The broad bands of multispectral scanners on Landsat are not well-suited for detecting chlorophyll suspended as phytoplankton, but they do have reasonable spatial resolution (90 m) and numerous images spanning several years. Landsat imaging is appropriate for assessing vegetative cover in wetlands. Imagery obtainable from the Thematic Mapper on Landsat 4 offers somewhat better chlorophyll detection in surface waters but is still inadequate. To improve characterization of the optical properties, chlorophyll content of inland waters, and perhaps to discriminate major types of light harvesting pigments requires a many band, imaging spectrometer.

Fluxes from land to inland waters are largely a function of land use in the drainage basin and hydrological conditions. Considerable information relating these two factors to water quality has been gathered in north temperate regions during the last decade. It is now possible to begin to make estimates of nutrient loading to lakes from remotely sensed watershed characteristics including land use and snow cover. Imaging visible and radar sensors and passive microwave sensors are required for such analyses. Much more research is needed on hydrologic measurements from space. In tropical regions, the pertinent information is lacking to relate watershed features to water quality.

Wetlands fringe many lakes and continents and form in floodplains along many rivers. They are foci for anaerobic, microbial activity and potential sources to the atmosphere of reduced gases. Two important factors that influence the biological activity are the maximum area flooded and the timing of the variations in water level.

TABLE A5. Observation Requirements: Inland Aquatic Resources

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Wetland area and flooded area	Biological productivity. Anoxic source areas for reduced gases. Nitrogen fixation	Imaging, multiband radar and visible sensors, 30 m resolution, daily-biweekly
Phytoplankton chlorophyll and biomass	Biological productivity spatial heterogeneity	Imaging, multiband visible sensor (e.g. Thematic Mapper, Imaging Spectrometer, Fluorescence Line Imager) 30 m resolution, daily-biweekly. (see Appendix A11)
Land use in drainage basins	Nutrient and sediment loading (relates to quality of water and productivity)	Visible and Radar Sensors (e.g. MSS, TM, SAR) 30 m resolution, monthly-yearly. (see Appendices A18 and A21)
Runoff and related hydrological parameters	Nutrient and sediment loading	Thermal IR, visible, microwave, daily-weekly. (See Appendix A1)
Surface temperature	Hydrography, evaporation and productivity	Thermal IR, 30 m resolution, daily-weekly

Remote sensing with imaging visible and radar systems is one of the few practical approaches to estimate the great extent of the wetlands and of their flooding. Synthetic aperture radar with multiple bands and look angles is necessary to examine wetlands and flooded areas.

Fluxes of P, N, S and C from land to oceans is primarily via fluvial transport. To improve estimates of fluvial transport requires repetitive sampling of major, representative rivers for at least a decade. A minimum group would include tropical plains rivers with forested basins (Amazon, Zaire), tropical plains rivers with savanna predominant in their basins (Magdalena, Niger), mountain rivers with high total suspended solids (Chang Jiang [Yangtze], Ganges; Mekong), arctic rivers (MacKenzie, Lena, Yukon), and rivers in the industrialized north temperate region (Mississippi, Rhine). More than one river in each group is necessary to evaluate the homogeneity of each group. A complementary approach to the estimation of fluvial transport to the ocean is to extrapolate export per unit area of land in various ecosystems based on data from lower order rivers and streams. This approach is potentially confounded by the biological processing of organic matter and nutrients within the river system.

To measure fluvial transport requires almost continuous monitoring of discharge and periodic collection of dissolved and particulate material. This sampling should be stratified to include more samples during floods than during base flow. A long-term program is necessary because the intensity of floods is erratic and extraordinary floods carry a disproportionate load. Discharge measurement is based on changes in stage and current profiles in a known cross-section of river. Remote sensing of stage height and flooded area is feasible but requires a satellite-mounted SAR sensor with 50 m in resolution. Remotely sensed estimates of current velocity based on the slope of the river's surface may be possible in some rivers. To test this in appropriate rivers and to measure currents in other rivers, ground-based flow meters must be installed. These devices can operate automatically and telemeter their output to a central location via satellite.

FOREST ENVIRONMENTS

Paul Zinke

SCIENTIFIC OBJECTIVES FOR THE 1990s

The application of remote sensing measurement techniques to scientific questions involving forests is a necessity because of the extent of forests, their variability, and the need to measure their interaction with environmental processes. The synoptic view given by remote sensing data of the extent, variability, and relation to environmental processes involving energy balances, disposition of water, and tree growth in relation to elemental storage of carbon, nitrogen and other essential elements is essential to understanding the forest in a scientific way. The ability to make comparisons in these properties at various intervals allows the determination of process functions and rates where the forest affects environmental properties.

The ultimate objective in using these data is to define the extent of the forest and wildland resource, to determine the changes that are occurring in the resource due to utilization by man under conditions of changing market and population demands, and to evaluate the correlated changes occuring in various environmental properties influenced by forest vegetation on a local as well as global scale.

Many of the scientific questions being asked about the role of forests and the effects of man made alteration of forests on environmental properties are related to the extent of the forest in its role of influence upon energy disposition and the attendant microclimatic effects, the loss of water by evapotranspiration, or effects on surface runoff and water yield. The comparative influence of forests on carbon and nitrogen cycling; and the interaction between forests, soils, and geologic substrate in geo-chemical cycles of various elements can be better understood using remote sensing data of the type which can be provided by Earth Observing System.

These data will be utilized in a procedure of successive nesting of the information, from the extensive synoptic coverage of System Z to the ultimate detail of the same parameters verified by ground based sampling plots. This method of nested plots in data matrices of increasing order of scale has been implicit in forest and natural resource scientific utilization of remote sensing data since its initiation decades ago in aerial photo interpretation. A present example has been in the radar survey of the extent and nature of the Amazon forest conducted by Projetto Radam (Department of Mines & Energy, Government of Brazil). The survey consisted of complete SLAR coverage of the entire area at a detail of 1/1,000,000, with finer detail at 1/250,000, and finally sample areas within this scale conducted at 1/1,000 with associated measurements of ground based information concerning the forest.

There are many ground based data concerning forests; their growth rates and associated environmental parameters which need to be linked to various orders of scale up to the global level which will be provided by EOS. This will allow the beginning of a solution to questions currently of importance that regard the effects of forest land use on global cycles of carbon and water, climatic changes, cumulative erosion rates over large watersheds; and associated changes in elemental cycling and water quality.

Most of the scientific questions involving forests are concerned with the role of forests in maintaining environmental properties, or the change in such properties when a forest is modified by man. These are either atmospheric or soil properties. Examples of the types of questions asked are:

1. How do forests on a broad scale affect precipitation and what effect will, for example, extensive clearing of forests for alternative uses have on this?
2. What effects do forests have on local and regional energy balances and how is this reflected in local and regional climate?
3. What is the role of forests as a sink or source for carbon dioxide?
4. How are water quality parameters such as stream or lake water temperatures, turbidities, etc. affected by land use practices which alter vegetation and forest cover on watersheds?

Most questions concerning forests involve the measurement of some property such as canopy or surface temperature, albedo, tree or foliage density, under a control or base line condition and under an altered condition. This can be done either by change detection over time, or by comparative evaluation of areas similar in conditions except for the presence or absence of forest.

The properties are usually measured as an *intensity factor* averaged over the unit area, and a *capacity factor* involving the extent of areas within similar range of property magnitude.

The *intensity factors* are those factors such as biomass or elemental storage per unit area. Also magnitudes of energy balance or water balance parameters for a unit area are such intensity factors. The *capacity factor* in a landscape sense is the areal extent of the level of the parameter concerned. The Earth Observing System's data are needed for quantification of both of these factors. Intensities of various wave lengths measured will be correlated with intensity factors through correlation with ground measurements at sampling sites. The areal extent, or *capacity factor* is determined by a class interval in such measures and the areal extent of the level.

The information offered by past satellite systems such as Landsat and the Thematic Mapper, along with System Z data are all needed to answer the scientific questions related to forest and land use change and their effects on environment. The rates of change of the various intensity factors, and their capacity factors as areal extent take place on a time scale of years. Thus to know the rate of change of tropical forest cover due to land use change it will be necessary to couple data observations that span a decade. The System Z observations made in the 1990s will need comparison with Landsat and Thematic Mapper data from the early 1980s.

The need for an adequate time base, on the order of one decade, also presses the need for adequate archiving as well as retrieval facilities for data from Landsat, Thematic Mapper, and other similar data, along with the new System Z data. In effect, the Earth Observing System is as much a data management system as well as a data gathering system.

OBSERVATIONAL REQUIREMENTS

These are essentially those needed in assessing the hydrologic cycle, the energy balance and biogeochemical cycles. These have been listed in the table of instrument requirements for forest and vegetation studies.

For any of the instrumentation the desirable data will be continuous overall coverage to a 1 km^2 minimum area, returning at least twice a month with an additional capability of data to a 30 m or 50 m pixel size covering a 1/2 degree swath, to be recorded only at designated times (or with cloud free, haze free conditions) and areas.

Data should be made available in form compatible with existing Landsat data tapes.

An Example

An example of a typical study that could be made

TABLE A6. Observation Requirements: Forest and Natural Vegetable Change Related Measures

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Mass and energy flux, short wave-long wave in and out, disposition of net all wave as in sensible heat or latent heat	Energy balance components Forests and natural vegetation Effects of forest clearing on local and regional microclimate disease vector propagation	50-60 m pixels, short wave, long wave to IR, at least monthly Surface temperature, albedo, thermal, H_2O vapor, 50-60 m pixels at least monthly
Hydrologic cycle components Precipitation Evapotranspiration Runoff Soil moisture storage Snow storage	Local and regional water balance determinations for major rivers as affected by land use and forest clearing	Microwave measurement, 1 km^2 liquid water. Water vapor-atmosphere. River and standing water measures. At least monthly
Vegetation density and structure and biomass determination	Relation to vegetation variables to elements of the energy balance and water balance	60 m pixels multispectral channel and ratio analyses
Inferred soil characteristics	Carbon and nitrogen storage in soils	Relating ground based measures to classification strata derived from spectral ratios
Vegetative condition	Assessment of vegetative condition, stress effects (water, disease, nutrients). Species types. Annual cycles and perturbations of remote sensed data related to phenology of trees, (growing period, deciduousness, etc.)	30-60 m pixels, multispectral, weekly observations

would be to determine the extent to which a large forest region such as the Amazon tropical forest, or the forest of northern Zaire is a water source. This would involve a determination of a water balance for that forest with measurements of precipitation, an estimate of evapotranspiration loss. This would involve a determination of net energy input to the forest canopy, and its disposition into latent heat (evapotranspiration) and sensible heat for which canopy temperature would be an index. Determination of atmospheric water gradients over the forest would be needed, presumably determined with lidar profiling of the regions and the downwind plume of moisture laden air. Transport rates of airborne moisture to and from the forest region would need to be determined, along with the trajectory to the point of departure from the water balance region being studied.

SUMMARY

Scientific problems involving forests at the present time are focussed on the effects of the changes in forest cover on climate, hydrology and elemental cycling on a global basis. The present perturbations in the carbon cycle are an example in that the question of the role of forest clearing on release of carbon dioxide from stored organic matter is a matter of current debate. The Earth Observing System data will be essential in determining local intensity of such storage, as well as areas extent of such amounts and their changes. A tabular summary of observations, problems, and measurement characteristics is presented in Table A6.

LAND BIOLOGY

Edward T. Kanemasu

SCIENTIFIC OBJECTIVES FOR THE 1990s

The advancing technology of our civilization on Earth affects our environment on a local, regional and global scale. Local effects can feed into larger scale effects because of positive feedbacks in our system. Our ability to understand, quantify and predict the large scale and long-term effects of our technology is truly mind boggling. The understanding of these effects, which is paramount to our quality of life on earth, will depend upon our ability to interact with scientists from the biological, atmospheric, oceanographic and geological sciences and develop a common communication system and unified objectives.

Energy Balance

The major factors affecting human environment are related to the flow of energy and mass in our biosphere. The cycling of minerals provides food and fiber for animal and human consumption. The flow of water from our aquifers through plant roots and to the atmosphere cools the plant surface, carries nutrients and cycles water into our atmosphere for distribution across the landscape. The partitioning of energy by the surface determines its productivity and environment.

Biological Productivity

The rate of diffusion of CO_2 and water vapor to and from plant organs is controlled by the stomatal openings which are in turn regulated by the organ's water balance (in most cases, plant leaves). Therefore, the availability of water and the plant's ability to extract water from the soil water reservoir strongly influences transpiration and photosynthesis. The availability of soil water is not only dependent upon the plant and soil hydraulic properties but also the plant's ability to partition photosynthate to below ground organs (roots) for improved extraction. In turn the partitioning of photosynthate is dependent upon the stage of growth (ontogeny) of the plant. Limited soil water supply caused by lack of precipitation or high evaporative demand can result in decreased photosynthesis (growth). Subsequently leaf growth is reduced and abscission of leaves results, thereby transpirational cooling is reduced and the plant increases in temperature. Concurrently, one usually observes an increase in soil temperature. This in turn increases the sensible heat to the atmosphere and air temperature increases. This air mass then moves into the surrounding area and becomes a source of energy (and possibly stress) for the adjacent ecosystem. In addition, the increase in soil temperature can affect biological activity as well as biogeochemical cycling. Therefore, a change in the energy balance of one ecosystem can impose significant environmental effects on another.

A desert biome will have a vastly different energy balance than a forest or grassland or cultivated field. The quality and quantity of vegetation will depend on its surroundings. Obviously, deforestation or desertification have large impacts on that particular area itself but its sphere of influence extends beyond its physical boundaries. The flux of CO_2 and water vapor are significantly altered as is the flow of nutrients in that ecosystem. In addition the runoff and sediment movement is changed which drastically alters the aquatic environment downstream. Further, large scale effects are due to changes in albedo which affect the atmospheric energy balance and subsequently the climate. It is this particular interaction between land surfaces, atmosphere and oceans that we propose to understand, quantify and model.

Obtaining estimates of energy balances of vegetated surfaces from space will be a major concern in 1990s. It will be important that multitemporal spectral data (visible, near infrared, thermal and microwave) be acquired on a 3 to 5 day cycle during growing season. Therefore, surface energy balance models can be used to estimate daily sensible and latent heat fluxes from the surface. By incorporating the latent heat flux (evapotranspiration) into the water balance, estimates of profile soil moisture can be made.

Remote Sensing

There is a general understanding that potential net primary productivity is dependent upon the amount of photosynthetic light (visible wavelengths) that is intercepted by the plant. This amount of photosynthate produced per unit of energy (photons) intercepted is dependent upon the plant species. Drawing from research conducted on cultivated crops during LACIE and AGRISTARS programs, we recognize the capability of spectral reflectance in the visible and near infrared wavelengths to assess green leaf area index (ratio of leaf area to soil area). This has been a tremendous advancement because green leaf area and its duration is strongly correlated to growth and economic yield. Even though for most plants the leaves are the intercepting plant organ, the amount of intercepted light is also dependent upon the morphology of the canopy. Thus knowledge of the foliage angle and distribution is required. Radiative transfer theory predicts that one can estimate these canopy parameters given that one can obtain spectral reflectance from different viewing angles. It is important that these measurements be taken over a relative short time period (1 hour) because of the dynamic nature of the canopy. The structure of the canopy can change with sun angle and water stress.

It is this dynamic nature of the plant which we wish to capture because it describes how the plant is responding to its environment, thereby providing information about its environment (profile soil moisture, water stress, disease, insects, etc.). In addition, these canopy parameters obtained from spectral measurements will provide clues for identifying plant types from space.

A field's variability in its spectral characteristics may provide detail information about the plant's previous experience such as winterkill, flooding, fertilization, tillage, and stresses (water deficit, pests, disease, etc.). This is due to nonuniform advance of these factors across a given agricultural field.

The plant itself is a sensor of its environment; thereby, allowing its spectral nature to divulge characteristics about water deficit, soil condition, disease and pest infestations, and fertility status. It is this particular science that may be exploited in the 1990s.

OBSERVATIONAL REQUIREMENTS

We are primarily concerned with the flow of mass and energy in the various ecosystems and to develop an understanding of the interactions among them. It is this interaction that can seriously affect the human environment where a subtle change in one ecosystem can cause major changes in another, thereby placing our environment on an intrepid path. The principal observational requirements are summarized in Table A7.

The energy balance of a surface unlocks many questions concerning the interactions between the atmosphere and the underlying surface. The partitioning of energy by that surface is dependent upon the microclimate, vegetation and soil. We envision that measurements would be made on specific sites and these sites would then be selected to represent a specific ecosystem. The primary fluxes of sensible and latent heat would need to be measured. There are various micrometeorological techniques that are available to evaluate these fluxes. Because latent heat flux (evapotranspiration) is a physiological as well as a physical process, we must be concerned with the physiological responses of the vegetation present. Therefore, the nature of the vegetation (specie and leaf area) are required in order to estimate or predict how the surface partitions its energy. The non-vegetation portion of the surface must be quantified for it interacts with the vegetation as well as with the atmosphere. There are many biophysical characteristics of the surface that can be addressed from remote sensing (e.g., leaf areas, phytomass, canopy morphology and temperature). Vegetation amounts are highly correlated to the red (630-690 nm) and near infrared (760-900 nm) wavelengths. These vegetal amounts are important because they distribute energy different than water and land surfaces. In addition, vegetation is dynamic; therefore, depending on the specie, temporal coverage is required to quantify their activity. In the study of biological activity, temporal

TABLE A7. Observation Requirements: Land Science

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
1. Leaf area index, phytomass	Latent heat and carbon dioxide flux, phytomass of major ecosystems	Visible, near infrared, microwave, 30 m resolution, 1300-1500 hrs., every 3-5 days, selected sites
2. Plant morphology	Light interception, specie identification, stress identification	Visible, near infrared, microwave, 30 m resolution, 1300-1500 hrs., every 3 days, 3 view angles, selected sites
3. Morphology and leaf area	Spatial variability of small land units for estimates of within field plant stress and erosion	Visible, near infrared, microwave, 10 m resolution, 1300-1500 hrs., every 3 days, selected sites
4. Soil moisture	Latent heat, productivity, energy balance	Microwave (0-5 cm layer) 30 m resolution, daily measurements
5. Surface temperature	Energy balance, drought and desertification	Thermal IR, 30 m resolution daily measurements at mid-day

coverage is a crucial parameter. It is this activity or reponse that we desire to understand. In some species and environments an overpass every 3 days will be required in others one every 30 days is sufficient. Vegetation is not uniform (horizontal) but changes in specie composition, phytomass, and structure occur in response to microclimate and soil. Therefore, transition zones occur because of certain limiting factors (water, temperature, nutrients, disease, insects, etc.). The dynamic behavior of these regions are of interest to the global habitability concept (i.e. desertification). In these boundary areas and other small production systems (e.g. subsistence agriculture in lesser developed countries) high spatial resolution (10 m) can be important. In many other situations, a 30 m resolution will be sufficient.

Knowing the biological productivity of an area is essential to the cycling of nutrients and carbon, the energy for human and animal activity and health, and the partitioning of energy. The biological productivity is highly dependent upon the interception of radiant energy in the visible wavelengths. The incoming energy can be estimated from solar radiation. The amount that is intercepted is dependent upon the leaf area and how these leaves are displayed with respect to the sun. Leaves (photosynthetic active organs) are not fixed but move in response to the sun, water stress, and biological stresses. The morphological changes in the canopy provide additional evidence for purposes of specie identification, stress assessment, and leaf area determination. Radiative transfer theory allows one to estimate leaf area and leaf angle from different view angle measurements (3 view angles). These measurements should be made on the same piece of real estate at approximately the same time. The atmospheric effects on the measurements would need to be determined; therefore, additional measurements (different wavelengths) will be required.

In assessing vegetation amount, the soil presents a confounding factor which must be minimized. A linear combination of Landsat bands has been successful in separating soil from vegetation. Narrow wavebands and/ or more wavebands over a wider range of wavelengths may provide even better separation. Presently, there is no reason to believe that the TM (Thematic Mapper) wavebands are not sufficient for estimating vegetation amounts. Certainly, more research is required on the spectral nature of vegetation and its response to the biophysical characteristics of the foliage. The thermal channel (10400-12000 nm) provides additional information concerning stress. Vegetation temperatures elevate when their water transport system is affected by water deficits, disease, insects, etc. The microwave wavelengths ($\sim$5 GHz) can provide useful information about canopy structure for specie identification. In addition, evidence indicates that while the optical wavelengths are useful for assessing low leaf area situations, the microwave may be better in the high leaf area canopies. In situations where cloud cover is prevalent, microwave may be the only sensor that can obtain useful information about the surface.

It should be recognized that the availability of daily meteorological data will play an important role in addressing issues in the 1990s. Solar radiation is one of the most important meteorological parameters. It is the major source of energy on Earth. Obtaining adequate global coverage of solar radiation data has been a problem, continued efforts to use other satellites (GOES, NOAA etc.) for estimating solar radiation will be important. The other meteorological parameter that exhibits large spatial variability is precipitation. The use of satellites to estimate precipitation between weather stations will be necessary for many remote areas where weather stations are widely distributed.

TROPOSPHERIC CHEMISTRY

Volker Mohnen

In this discussion of tropospheric chemistry problems in the 1990s, we assume that the global research focus now discussed within NASA ("Global Change: Impacts on Habitability. A Scientific Basis for Assessment." JPL D-96) and the National Science Foundation ("Global Tropospheric Chemistry: A Plan for Action." National Academy Press, Washington, D.C., 1984) continues to unify the scientific community in order to gather complimentary measurements using ground stations, air borne platforms and satellites. We begin to recognize that the human race is being rapidly confronted with increasing limitations imposed by the finite nature of our global habitat. Activities of man now constitute a major direct and indirect influence on the chemistry of the troposphere. The assessment of our own impact is hampered, however, by a lack of understanding of underlying physical, chemical and biological factors which regulate the "global system." The troposphere constitutes a medium that is vital for the completion of major biogeochemical cycles essential to life.

On a decadal or greater time scale, the atmosphere, land and sea operate as a coupled system not only in their physical interactions, but also through chemical and biological processes. It has become clear that the troposphere is an integral component of the planetary life support system—receiving, transporting, transforming and depositing substances that either contribute to the efficiency of the system or deleteriously perturb it. Perturbations can be expected to increase in frequency and variety during the next several decades. It is necessary, therefore to understand the fundamental processes that control the chemical composition and cycles of the global troposphere and how these processes and properties affect the physical behavior of the atmosphere. The long-term information needs for tropospheric chemistry are:

- To be able to predict tropospheric responses to perturbations, both natural and anthropogenic, of these cycles and
- To provide the information required for the maintenance and effective future management of the atmospheric component of our global life support system.

The processes controlling global tropospheric biogeochemical cycles include:

- The input of trace species into the troposphere,
- Their long-range transport and distribution as affected by the mean wind and vertical venting,
- Their chemical transformations, including gas to particle conversion, leading to the appearance of aerosols or aqueous phase reactions inside cloud droplets, and
- Their removal from the troposphere via wet (precipitation) and dry deposition.

To accomplish the above goals, major research and measurement efforts must be initiated focusing on atmospheric *processes* and on atmospheric *trends*. To achieve progress, the following key questions need to be answered:

1. What is the biological source strength of chemical substances in the troposphere for carbon, sulfur, nitrogen and halogen compounds? Primary emphasis should be placed on investigations of temperate and tropical forests and grass lands, intensely cultivated areas, coastal waters and salt marshes, continental shelf zones, upwelling zones, open ocean regions, tundra regions and biomas burning. These overlap to a considerable extent with the biogeochemistry questions raised in this document, since the parameters and species of interest are identical.
2. What is the source strength of primary aerosols (dust, fossil fuel combustion including biomas burning) on a regional and continental basis? Of particular interest are the deserts of the world and fallow land.
3. What is the global distribution for tropospheric species (gases and aerosol) in key chemical cycles. Major candidates are sulfur, nitrogen, carbon and halogen compounds. To assess global trends it is essential that observations extend over a long time scale. An additional need for long-term monitoring efforts arises from the fact that the dynamic biogeochemical equilibria among the major pools of carbon, nitrogen, sulfur and halogens may take decades to adjust. Therefore, man induced perturbations and the system's responses constitute an ongoing biogeochemical experiment of continuing duration on a global scale.

To help in data interpretation it is desirable to have available concurrent measurements of parameters of the hydrological cycle. These include water vapor, cloud cover (including cloud height and any layering) and the precipitation field. Water in its various physical states plays a dominant role in atmospheric chemistry: water vapor is the source for the all important hydroxyl radical that is central to gas phase chemistry. The hydroxyl radical initiates the noncyclic chemical transformations of major gas species including sulfur and nitric acid. Water vapor is also the source for the hydrogen peroxide molecule that is a crucial aqueous phase oxidizing agent. The condensed phases of water (cloud and precipitation elements) host and promote chemical transformations of species involved in most tropospheric cycles, including sulfur, nitrogen, carbon and halogen compounds. During phase transitions, latent heat is released or attained. This generates vertical motions over a range of scales and magnitudes, from fair weather cumuli that mix boundary layer air with air just above the boundary layer to severe thunderstorms that may penetrate the tropopause and mix tropospheric and stratospheric air or generate down drafts that transport mid-tropospheric air to the surface. Evaporating hydrometeors leave behind a particulate and gaseous residue that is considerably different from the original state. It is obvious that clouds do significantly influence the global distribution of gases and aerosols due to vertical transport and chemical interactions with the surrounding medium.

It is also important to have corresponding ozone measurements available. Ozone is an important atmospheric constituent in its own right, signaling the photochemical state of the troposphere and transport of air from the stratosphere. Ozone also is ultimately connected with the fast photochemical cycle and, as such, of intense interest to tropospheric chemists. Indeed, the study of this fast photochemical cycle involving ozone, oxides of nitrogen, carbon monoxide and methane is one of the key research tasks in tropospheric chemistry addressing chemical processes that govern the formation, the loss and hence the tropospheric concentration of the all important hydroxyl radical. The relevant research problem can be formulated as follows:

4. Test photochemical theory through field investigations of photochemically driven tranformation processes. Investigations over tropical oceans and rain forests with additional studies in midlatitudes are particularly important.

Other *process-related* questions concerning the oxidation of sulfur, nitrogen and carbon compounds and their subsequent removal by wet and dry deposition need to be answered in order to refine the overall global budget for these substances. The problem may be stated as follows:

5. Investigate non-cyclic transformations and wet and dry removal processes for trace gases and particles. Research should be directed not only toward evaluating chemical fluxes to land and water surfaces, but also toward a fundamental understanding of aqueous-phase reaction mechanisms and scavenging processes.

Modeling efforts must be a major component of any global tropospheric chemistry project. In addition to current modeling efforts, there is a great need to focus development of tropospheric chemistry systems models in order to evaluate field observations. A wide range of models of individual processes important for tropospheric chemistry must be developed. Based on these efforts comprehensive global models should emerge that include all the relevant chemical and meteorological processes. These model development and global measurement efforts are necessarily symbiotic; progress in each area is dependent upon contributions from the others.

The field of tropospheric chemistry is confronted by an array of identified environmental problems for which public policy makers at the state, national and international level are demanding research solutions. It is generally suspected that even more problems that derive from man's activities are on the horizon. Future environmental issues and policy discussions on a regional to global basis will require a deeper understanding of the entire global atmospheric chemical system. With this in mind, research into understanding the major biogeochemical cycles as they propagate through the atmosphere and monitoring of key chemical species for which both man made and natural sources exist assumes significant importance and justifies major commitments by governments. The key questions in tropospheric chemistry are indeed addressing major problems of the future integrity of our global habitat.

Appendix: Global Distribution of Tropospheric Trace Constituents

Before we can claim an understanding of the natural or perturbed troposphere, atmospheric scientists must be able to follow the flow of chemicals through it. There are many research questions that require information on the intensity, size, and variability of sources of tropospheric chemical species, what factors control the ambient concentration of a certain chemical, or why the concentration is increasing or decreasing in time, or how human activity will alter the source in question. Major efforts need to be undertaken to evaluate biological sources of chemical substances in the global troposphere. The objective of such studies would be to evaluate the chemical fluxes to the troposphere from critical biological environments (biome) and to determine the factors that control these fluxes. In addition to this, it is necessary to establish a global tropospheric chemistry sampling network with the additional objective to obtain atmospheric chemical data that can be used to identify important meteorological transport processes and to validate and improve the ability of models to simulate the long-range transport, global distribution and variability of selected chemical species. Furthermore, equally important objectives are (1) to determine the distribution of those chemical species that play important roles in the major chemical cycles of the troposphere, and (2) to detect, quantify and explain long-term trends in en-

TABLE A8. Global Distribution*

Cycle	Gas	Lifetime	Source	Use		Availability (from ground based stations)	From Aircraft Platform	Satellites (Remote Sensing)
	F-11	L	A	T-R	Possible candidates for low tech measurements in remote regions	YES	YES	
	F-12	L	A	T-R		YES	YES	
	F-21	M	A	T-R		YES	YES	
	F-21	L	A	T-R		YES	YES	
	CH_3CCl_3	M	A	T-R		YES	YES	
	C_2Cl_4	S	A	T-R		YES	YES	
	C_2HCl_3	S	A	T		YES	YES	
Carbon	$C\,H_4$	M	N	T-C-R		YES	YES	YES
Carbon	Alkanes C5	S	A&N	C		YES	YES	
	CO_2	L	A&N	R		YES	YES	YES
Carbon	CO	S	A&N	C		YES	YES	YES
Sulfur	COS	L	A&N	C		YES	YES	
Sulfur	CS_2	S	A&N	C		YES	YES	
	N_2	L	A&N	R		YES	YES	YES
	O_3	S	A&N	T-C-R		YES	YES	YES
	H_2O	S	N	T-C-R		YES	YES	YES
Nitrogen	NO	S	A&N	T-C	Candidates requiring high tech instru. or long-term filter samples	YES	YES	
Nitrogen	NO_2	S	A&N	T-C			YES	
Nitrogen	HNO_3	S	Secondary product	T-C		YES		
Nitrogen	NH_3	S	A&N	T-C		YES		YES
Sulfur	SO_2	S	A&N	T-C		YES		
Sulfur	$H_2\,S$	S	N	C		YES	YES	
Sulfur	DMS and other organic sulfur	S	N	C		YES		
Fast photochem. theory	OH	Very Short	Secondary Products	C	High tech			
	H_2O_2	S		T-C				
	$C\,H_3OOH$	A		C				
	$CH_2\,O$	S		C				
	Particles	S		T-C-R	Possible candidates for low tech measurements in remote regions	YES	YES	YES
Halogen	Na_+, Cl_-		N			YES		
Sulfur	$SO_{4=}$		A&N			YES		
Nitrogen	NO_{3-}		A&N			YES		
Nitrogen	NH_{4+}		A&N			YES		
	Soil		A&N			YES		
Carbon	Carbon (Total & elemental)		A&N			YES		

* For reasons of brevity, not all important species are listed.

Note: A set of standard meteorological observations must be made concurrently. In addition it is desirable to have available information on cloud cover, height and on precipitation quantity and quality, where appropriate.

Code: A: anthropogenic, N: Natural, T: Transport, C: Cycles, R: Radiatively active, S: Short (~ month), M: Medium, L: Long (~ decade) Lifetimes vironmentally important trace gases and aerosols.

The species of interest are listed in Table A8. A number of very important species are omitted at this time for the sake of brevity. Each substance in Table A8 is classified as to its major source (anthropogenic or natural), the primary application of the data (i.e., the development of transport models, importance to climatic processes, or elucidation of chemical cycles), its relative lifetime in the atmosphere (short, i.e., months or less; medium, i.e., a few months to a few years; or long, i.e., a few months to a few years; or long, i.e., more than a decade) and the availability of appropriate measurement technology. For a global ground based measurement network there exist sufficient low technology apparatus to begin noncontinuous operation representative remote sites or source oriented sites (grab samples, filter samples, etc.). In general, however, there is need for substantial technology development. The principal observational needs for tropospheric chemistry in the 1990s are summarized in Table A9.

Ideally, spaceborne remote sensors could provide near global measurements and thus satisfy the ultimate goal of obtaining a three dimensional distribution of certain atmospheric trace constituents. It is to be hoped that this approach will eventually provide the tropospheric chemistry community with the opportunity to iterate a variety of distribution measurements with evolving mathematical models of the troposphere.

TABLE A9. Observation Requirements: Global Atmospheric Chemistry Cycle

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
CO_2, CO, CH_4	Understanding biogeochemical cycles	3 weighting functions in troposphere 0-15 km, 10 km horizontal resolution, CO_2 resolution $\pm$ 0.3 ppmv, CO resolution 10 ppbv to 0.3 ppmv, CH_4 from 100 ppbv to 3 ppmv
OH	Tropospheric lifetimes of atmospheric chemicals such as CO, CH_4	0.5×10^6 molecules/cm^3 lowest detectability
NO_2, NO, NH_3, N_2O	Nitrogen cycle	0.1 ppbv lowest detectability
HNO_3, NO_3	Nitrogen cycle	0.05 ppbv lowest detectability
SO_2, H_2S, COS and other sulfur compounds	Sulfur cycle	0.05 ppbv lowest detectability
H_2, H_2O	H cycle	H_2 to 0.02 ppmv, H_2O from 1 ppmv to 5×10^5 ppmv
O_3	Oxygen and oxidant cycle	O_3 from 2 ppbv to 2000 ppbv
Aerosols	Aerosol cycle (including sulfur cycle and nitrogen cycle)	From 0.1 $\mu g/m^3$ to 100 $\mu g/m^3$
Temperature, wind velocity, clouds, rainfall rate, lightning	For interpreting all cycles	1 km vertical resolution, wind to 1 m sec^{-1}

GEOLOGY

Raymond Arvidson

SCIENTIFIC OBJECTIVES FOR THE 1990s

1. Objectives outlined assume that the following will have been accomplished in the 1980s:
   - A. Landsat TM coverage over land areas completed and available. Work done on using multispectral data to map rock mineral assemblages.
   - B. SIR-A; SIR-B flown and multi-incidence angle capability utilized to characterize roughness. Some X-band and L-band data acquired simultaneously.
   - C. Large format camera data analyzed for selected areas.
   - D. Progress made on physical basis for utilizing vegetation to map soil/bedrock characteristics (i.e., geobotany becomes quantitative science).
   - E. Some high resolution multispectral imaging done in reflected part of spectrum and in emission part, from low Earth-orbit system perhaps shuttle. Spectral resolution in reflected part of spectrum about 0.02 micrometers. Utility for mineral assemblage and vegetation mapping demonstrated.

2. *Objective One*: Global distribution, geometry and composition of continental rock units.

The record of the deformational history of the Earth is largely contained in the nature and geometric configuration of the rock units contained in the continental crust. The reason is that oceanic crust produced at mid-oceanic ridges is consumed back down into the mantle along subduction zones at rates of typically centimeters/year. Consequently, although the oceanic crust occupies 70% of the Earth's surface, it only provides a record for the last 200 million years of geologic time. The continental crust is too buoyant to be subducted and as a consequence records a much longer history (over 2 billion years) of rifting, collision, downwarping, and uplift associated with plate tectonics and a convecting mantle. That history is recorded in the characteristics (geometry, age distribution, composition) of the rock units that make up the continental crust. It is important to note that most of the Earth's nonrenewable resources, particularly ore deposits, occur within the continental crust. Consequently, a better understanding of the nature and distribution of crustal units would both increase our understanding of the deformational history of the Earth and the location and mode of emplacement of nonrenewable resources.

The degree to which rock units have been mapped on the Earth varies considerably. Some areas in the United States have been mapped in detail while vast areas in third world countries, both desert and jungle, have only been mapped in a reconnaissance mode or not mapped at all. A remote sensing approach would provide the synoptic view necessary to systematically inventory poorly known areas. Utilization of Landsat 4 TM data, when and if the data are available, would improve the situation in arid and semiarid regions, where the data can be used to roughly map groups of mineral assemblages. However, it is clear that higher spectral resolution would be needed to separate most rock types and soils. Also, removal of the atmospheric contribution to the spectral radiance is very important in analysis of narrow band data. In addition, in vegetated regions other approaches must be taken, including use of variations in vegetation characteristics to map underlying materials. This field, usually called geobotany, is in an embryonic stage and considerably more work is needed to be able to utilize the reflectance of emission properties of vegetation to map underlying materials.

3. *Objective Two*: Morphology and structure of the continental crust.

The distribution of topography on the continents is a consequence of the history of exogenic (surface) and endogenic (related to interior) processes that have operated. These processes are influenced by the climatic regime and its variation through time, and by the tectonic regime and its variation. Thus, quantitative data on the distribution of elevations provides an important base for understanding both surficial and endogenic processes and their effects on the Earth's surface. In addition, these data are best utilized in combination with other data sets, such as meteorological data for understanding whether or not the present land forms are related to the current climate, or gravitational anomalies for understanding the extent to which structural features such as fractures and folds are indicative of a deep-seated crustal inhomogeneity.

The quality and quantity of topographic data for the continents is quite variable. Digital topographic data for the United States exist for elevations averaged over about 65 meters. For Canada, only 5 minute averages are available. Little data indeed are available for Africa or

Asia, regions that are important because of the recent tectonic events and the range in climatic conditions. Data that provide 100 m averages of elevation on a worldwide basis would be very useful. Consideration should be given to acquisition of such data using stereophotogrammetric techniques, with both optical and radar sensors.

4. *Objective Three*: Monitoring selected surface processes.

Processes such as rainfall and runoff, dust storms, erosion of coastal areas, volcanism, and tectonic events such as earthquakes occur often on Earth and in some cases pose severe hazards. The synoptic view provided from space allows a tradeoff of space for time, thus increasing the probability of detecting a surface process or its effects significantly above the chance of acquiring such observations on the ground.

Two kinds of objectives can be formulated for monitoring surface processes. A first objective could be to monitor events of opportunity that were scientifically interesting and posed a hazard. For example, following the crest of a flood wave in a river system, or the plume of debris injected into the atmosphere from a volcano, could be done from low Earth orbit. For this objective, an "all weather" capability would be needed, with the additional requirement for a pointable platform to be able to track events not beneath the ground track.

A second objective could be to monitor the results of some process of major scientific significance and economic interest, such as effects related to desertification. In this case, a requirement would exist to collect a variety of data, such as soil moisture, biomass content, susceptibility of surface material to erosion and transport, and meteorology data. This kind of objective demands that data management be streamlined and that documented data sets be readily available, since a variety of data would be dealt with to test models and to document the phenomena.

OBSERVATIONAL REQUIREMENTS

Mapping soil, sediment, and rock characteristics for land surfaces requires use of visible, reflected, thermal and radio parts of the spectrum. The shorter wavelength, higher energy radiation associated with reflected solar radiation (0.4 to 2.5 μm) is of sufficient energy to provide information on mineral chemistry, since electronic transitions, charge transfers, and molecular vibrations are induced. For vegetation, the 0.4 to 0.9 μm region provides information on pigmentation, responses in the 0.9 to 1.2 μm region are related to cell structure, and longer wavelengths to vegetation water content. Subtle variations, such as shifts in the chlorophyll absorption located near 0.7 μm, have been shown to be related to variations in the amount of base metals found in leaves. Regions with higher base metal contents also seem to have plant cover that is subject to premature senescence, i.e., early onset of fall colors. Thus, the radiance values related to spectral reflectance can be directly used to map mineral assemblages in areas with minimal vegetation cover. In addition, reflectance data are valuable in some instances for geobotanical studies, i.e., mapping underlying materials from the vegetation signature. The number and spectral resolution needed for mapping are governed by the locations, depths and shapes of absorption features to be measured. Finally, the spatial resolution needed is governed by the requirements to be levied on the data–requirements related to understanding regional geological processes. Digital topography and atmospheric corrections are also needed.

The intermediate wavelengths corresponding to thermal emission can be sampled in the 8 to 14 μm atmospheric window. This part of the spectrum can be utilized with a broad band system to measure diurnal temperature variations in non-vegetated regions. The diurnal variations, when compensated for diffential solar heating due to topography, surface albedo, and atmospheric effects, can be used to compute thermal inertia. This derived parameter is related to the density, heat capacity, and thermal conductivity of materials within about ½ meter of the surface. Spectral emissivity is another derived parameter that can be extracted from thermal emission data. Emissivity variations are largely controlled by stretching between silicon and oxygen atoms. The wavelength of minimum emissivity shifts to longer wavelengths with increasing silicon content. Spectral emissivity data provide another method for determing mineralogy. This area is less well developed than the use of spectral reflectance for extracting mineralogy, primarily because of instrument limitations. Again, topographic and atmospheric effects must be removed.

The longer wavelengths used for X and L band radar are of low enough energy to mainly provide information on surface roughness at approximately the radar wavelength. Some information is also provided on dielectric properties of surface materials, with variations in soil moisture content dominating such variations. Variable wavelength and incidence angle side looking synthetic aperture radar data would thus provide information on surface roughness and moisture content. The first parameter is useful for mapping surface materials and the second parameter is a key to understanding hydrological processes.

Digital topographic data (elevation, slope angle, slope magnitude) are needed to correct reflectance, emission, and radar data. In addition, images of the topographic data provide fundamental information on the morphology and structure of the land. Topographic data could be collected with either a radar altimeter or a laser altimeter. The former would provide an all-weather capability.

Finally, the atmosphere both attenuates the remote sensing signal coming from the surface and it adds a term related to light scattered from atmospheric particles and into the sensor. Thus, to extract reflectance and emission data, simultaneous measurement of such parameters as atmospheric optical depth, scattering albedo, and phase function need to be obtained over the same wavelength intervals.

The observational requirements described above are summarized in Table A10.

TABLE A10. Observation Requirements: Geology

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
1. Surface elevation and slope (worldwide land areas once)	Morphology and structure of land surface; needed to correct SAR images for relief displacement; needed to correct for surface illumination scattering function and differential solar heating; i.e., needed to do 2-5.	Stereophotogrammetric reduction of optical or SAR images; radar or laser altimeter; ~100 m ground-width; ~3 m vertical accuracy.
2. Physical configuration of surface materials—thermophysical properties (arid & semiarid regions)	Map soil or sediment characteristics.	Imaging radiometer; 100 m IFOV, 10-12 μm channel to acquire diurnal temperature variations; broadband albedo also needed from 0.4 to 2.5 μm.
3. Physical configuration of surface materials—surface roughness and electrical properties (worldwide selected coverage)	Map bedrock, soil or sediment characteristics in arid and semi-arid regions; detect changes—for example, seasonal flooding effects in cloud covered areas such as Brazil.	Variable incidence angle, variable frequency (X and L) variable polarization SAR with 30 m cell size.
4. Rock mineralogy where soil or bedrock is exposed; vegetation pigment, cell structure, and water content in vegetated regions—from spectral reflectance. (Cloud-free one time coverage; repeated coveraged for geobotany desertification, etc.)	Distribution of rock and soil types on land surface; use of vegetation spectral reflectance to infer physical and chemical character of underlying soils and rocks.	Imaging spectrometer with 0.4 to 2.5 μm coverage; ~100 channels—selectable in number and gain; 10 nm spectral resolution; 30 IFOV; 1% relative radio-metric sensitivity.
5. Rock mineralogy where soil or bedrock is exposed—from spectral emissivity (arid and semiarid regions). (Possible utility to geobotany—not demonstrated at this time.)	Distribution of rock and soil mineralogy and physical state of land surface.	Thermal imaging radiometer with 8 to 14 μm coverage; ~10 channels with 0.5 μm spectral resolution and NEΔT of 0.4° at 300°K; 100 m IFOV.

NOTE: a) Visible, reflected IR, and thermal IR measurements are perturbed to a significant degree by atmospheric effects. The attenuation and scattering characteristics of the atmosphere at the times and locations of the observations must be known as a function of wavelength to remove the atmospheric effects from the signals.

INTERIOR OF THE EARTH

Roger J. Phillips

SCIENTIFIC OBJECTIVES FOR THE 1990s

The basic questions regarding the interior of the Earth for the 1990s will be a continuation and a refinement of the key questions presently being addressed.

Plate Tectonics

The basic tenets of plate tectonics have been accepted for 15 years. The outer rigid shell of the Earth—the lithosphere—is broken into a number of large rigid plates that are in constant motion with respect to one another. Plates are created at the ocean ridges and destroyed at some plate boundaries by collision or by subduction into the mantle. The plate motions are the boundary layer manifestation of the mantle convection system.

Given proof of the first-order theory, the relevant questions regarding plate tectonics relate to details of the motions and how they relate to mantle convection. Knowledge of the plate velocities needs to be refined in order to test detailed theories of plate dynamics. This knowledge will be gained, in part, by VLBI measurements. A long-term goal is to understand secular variation in plate velocities. The plates themselves are not totally rigid, and the nature of stress transmittal across the plates and deformation away from plate boundaries is not well known. The driving mechanism for the initiation of plate subduction is not understood, but once subduction is achieved, the pull of the subducting lithosphere is an important force. However, the relative importance of some of the other forces, such as push by the ridges, is a subject of debate.

Mantle Problems

That the mantle is in constant convective motion is both predicted by theory (super-critical Rayleigh number) and verified by the motion of the lithospheric plates. However, details of the convective motion are mostly unknown. Leading questions regard the planform, vertical structure, and time variation of the flow. Additionally, it is not known whether the entire mantle is one convection system or whether the motions are separated into distinct layers separated by thermally conductive boundary layers. Coupled with this problem is the fate of the subducted slabs—to what depth do they descend before being assimilated by the mantle?

That both the upper and lower mantle are laterally heterogeneous is known from seismology and from gravity observations. Whether these variations are due to thermal fluctuations associated with convection or compositional variations (primordial or otherwise) is an open question. The bulk composition of the upper mantle is fairly well constrained from seismology. Because of uncertainty in the higher pressure phases of mantle minerals, the composition of the lower mantle is not as well known. Of critical importance is the magnesium to iron ratio for the lower mantle and how it compares to that ratio for the upper mantle. This has strong bearing on our knowledge of the accretion and bulk composition of the Earth as well as the convection history of the mantle.

Core Problems

Fundamental problems concerning Earth's core include the mechanical properties of the inner core and the nature of the inner core-outer core and outer core-mantle boundaries. The identification of the light alloying element in the core is of extreme interest. If it is sulfur, it will vindicate certain cosmochemical theories for the formation of the planets. If it is potassium, it provides an energy source for driving the geodynamo. (Another energy source could be the latent heat of freezing of the inner core—is it enough by itself to power the geodynamo?) An adequate theory to explain the magnitude of the magnetic fields of the terrestrial planets is not available. By the 1990s we might expect such a theory to explain secular variations (including reversals) in the Earth's fields, so global observation of the main field over a long time-base is required.

Continental Structure

The Earth's continental crust is a direct result of the plate tectonic actions of collision and subduction. It is generally held that a large fraction of the continental crust is formed by the accretion of island arcs—those elongate zones of igneous activity that form by the partial melting of subducted lithosphere. Superimposed on the horizontal motions of plate tectonics are the vertical tectonics associated with sedimentary basin formation and continental penetration by convection plumes—the hot spots.

The growth history and thermal evolution of continental crust is not well constrained, nor is sedimentary basin evolution. The nature of the lower crust is poorly perceived, and knowledge of the properties of the lower crust would add greatly to our understanding of continent formation.

OBSERVATIONAL REQUIREMENTS

To answer the key science questions for the 1990s for the Earth's interior will require a coordinated effort involving theory, laboratory experiments, and observations on land, over the sea, and from space. The chief observational contributions will come from seismology, isotopic studies, heat flow, distance measurements and the potential fields (gravity and magnetic). Low altitude spacecraft have a stong contribution to make in the global, synoptic measurements of potential fields. In addition to spatial information, measurements of the global secular variation of the magnetic field is also required. Distance measurements from space could also contribute to an understanding of plate motion and deformation.

Since important geologic structure exists at all scales from meters to thousands of kilometers, geophysicists can successfully argue that global coverage is required at accuracies and horizontal resolutions that can never be achieved from space. On the other hand, acquisition of ground- and sea-based high-resolution gravity and magnetic measurements on a global basis is not a realizable goal due to both political and economic limitations. Additionally, space observation is a practical means of achieving accurate measurements of the long wavelength portion of the potential field spectrum. We must, however, address the question: "What additional improvement in precision and resolution of the potential fields observed by spacecraft can be gained over the GRM mission?"

In terms of distance measurements, the key question is whether space observations can contribute information independently of the ongoing ground based programs in terms of accuracy, coverage, or the economics of the measuring program.

As mentioned above, several different classes of observations are required to answer the key questions. The following discussion will be limited to observation by spacecraft.

Potential Fields

Two example problem areas that involve gravity field measurements and will contribute to the major questions are:

1. What is the nature of lateral density inhomogeneities in the mantle beneath the lithosphere and how can the density distribution be related to the planform of mantle convection?

This problem has been most closely tied to gravity anomalies over the ocean basins. In principle, theories of convective flow predict both the form of gravity anomalies and the deformation of the overlying lithosphere in response to the flow. While altimetric measurements yield fine scale resolution of the oceanic geoid, both altimetric *and* gravity measurements are required to fully separate internal density effects from dynamic effects of the ocean itself.

2. What is the structure of the lower crust and upper mantle lithosphere?

Seismology and gravity are often used to determine lithospheric structure. Large areas of the Earth have not had systematic gravity measurements so that a survey from space would provide fundamental information about lithospheric structure. For example, the only ongoing area of continental collision—the Himalayas—has extremely sparse gravity information and the availability of such data, along with some seismic control, would greatly improve our understanding of the structure of the zone of two colliding continents.

Magnetic field data from space promises to yield fundamental data on the structure of the lithosphere. Space derived data yields information on structure and composition of the lower crust and on the thermal structure of the lithosphere, both primary problems in geophysics. Structure and composition of the lower crust is determinable by magnetic field mapping insofar as these quantities are reflected in the ferromagnetic content of lower crustal rocks. Thermal structure is reflected in the lateral variation in depth to the Curie isotherm, the temperature above which magnetic induction is not possible.

Global monitoring of the magnetic field at least once per decade is required to accurately monitor the secular variation of the main field.

GRM Capabilities and Resolution Requirements

The anticipated accuracies and resolutions of the GRM mission are as follows:

Gravity field: 2 milligal and 100 km

Magnetic field: 2 nanotesla and 100 km

The following table (from "The Requirements and Feasibility of the GRAVSAT Mission," Report by GRAVSAT Users Working Group, NASA, August, 1980) lists resolution and accuracy requirements for major geologic features.

The requirements for magnetic field measurements are very similar, with the same ranges in Table A10 (with accuracies now in nanoteslas, not milligals).

As should be obvious from this discussion, knowledge of the geologic features of Table A11 is fundamental to attainment of the answers to the key questions regarding the interior of the Earth. The GRM will clearly resolve many of the geologic features noted, and thus will have a significant impact on our knowledge of the interior. To improve beyond GRM to meet the important but more restrictive resolution requirements of Table A11 will require an answer to the question: "Will the technology be such that, by the 1990s, potential fields can be mapped from space in the wavelength range 10

TABLE A11

	Resolution Required (km)	Accuracy Required (1 Standard Deviation) (milligal)
Sedimentary Basins	10-300	3-6
Mountain Ranges	20-1000	8-10
Subduction Zones	50-1000	10-12
Ocean Rise Volcanism	30-300	4-6
Other Oceanic Volcanism	30-1000	6-8
Shields	50-800	2-3
Mantle Convention	400-3000	2-10

to 100 km?'' A positive answer to this question clearly points the way to new potential field measurements from space in the next decade.

Distance Measurements from Space

Space platforms offer the potential to perform distance measurements over a wide baseline. The objective is to measure both plate motion and plate deformation, which on an annual basis varies from sub-millimeters to centimeters. Spacecraft distance measurements could most likely be carried out by laser or radio ranging (in time or frequency) to fixed ground station arrays. In simplest terms, the requirement is to measure the secular change in the distance vector between two (or more) points on the surface of the Earth. It is plausible to predict that by the 1990s baseline accuracies on the sub-centimeter scale will be required in order to provide significant increases in the knowledge of lithospheric motion.

The measurement needs described above for the Earth's interior are summarized in Table A12..

TABLE A12. Observation Requirements: Interior of the Earth

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Gravity field	Mantle convection, oceanic lithosphere, continental lithosphere, sedimentary basins, passive margins, etc.	30 km spatial resolution, 1 mgal accuracy, global coverage.
Oceanic geoid	Mantle convection, oceanic lithosphere	1 cm accuracy, global oceanic coverage.
Magnetic field	Crust and upper mantle composition and structure, lithospheric thermal structure, secular variation of main field, upper mantle conductivity	30 km spatial resolution, 1.0 nanotesla resolution, global coverage at least several times.
Continental topography	Necessary for interpretation and modeling of gravity field data	3 km spatial resolution. 3 m accuracy from averaging within 3 km blocks. global coverage of land masses.
Vector changes in geodetic array distances	Plate motion and deformation	1 cm accuracy in each distance component.

OCEANIC TRANSPORT

Robert Chase and Lawrence McGoldrick

SCIENTIFIC OBJECTIVES FOR THE 1990s

For life on the Earth, one of the more important effects of large-scale water movement is the moderation of global climate. Temperature extremes well beyond the present variations would be the norm for vast areas of the Earth if the oceans did not exist. The ocean is thought to provide this ameliorating effect by carrying a large fraction of the heat supply from the equator to the poles, thus limiting the large temperature variations that would occur, and by acting as a large capacity heat sink, thereby reducing the potential seasonal temperature ranges. At present, however, we lack real measures of the amount of heat carried poleward by the oceans.

The global ocean also plays a role in determining the abundance of carbon dioxide and its potential effect of climate. The oceans absorb some of the carbon dioxide from the atmosphere, reducing atmospheric heating rates. When the atmosphere is heated, the oceans will also respond to these increased temperatures. We cannot determine either the magnitudes or the rates of these exchanges, over the short and long term, without first acquiring a better knowledge of the large-scale, low-frequency water circulation and its response to changing atmospheric conditions.

It is precisely this same large-scale transport which is responsible for redistributing various chemical species within the oceans, in ways which we cannot now determine. The nutrients which support our fisheries, as well as many nefarious anthropogenic pollutants are carried together along our coastal boundaries, into the ocean interior, eventually to be cycled back to our shores and fishing grounds. Will they be returned to man at levels which we cannot tolerate; will our fishing grounds prosper or decline, what are the time scales over which we should expect these changes? Climate, fisheries productivity, pollutant cycling, are all valid societal concerns, which are controlled in part by oceanic transport.

Because of this central role played by the oceans, the question arises as to whether some feature of the ocean is changing to a degree that is affecting commensurate changes in the Earth's ecosystem. At this time, there is no way of addressing this question, since the present climatic state of the oceans is known only in the most primitive terms.

The processes which govern in the transport of heat and chemical species within the ocean are not only fundamentally important in the time-averaged sense, but also at a wide range of time scales. For instance, it has been shown that the Pacific sea-surface temperature can have an influence on the weather experienced over North America on time scales of weeks and years. Western boundary currents have been shown to be the return flow of water forced to circulate in great gyres by the wind stress exerted on the ocean surface. We do not yet know how the observed annual periodicity of these boundary currents is related to the annual cycle in the atmospheric circulation.

The oceans are a global phenomenon; the tools available to the oceanographer, however, have been best suited to studying the ocean at a few discrete points or, in rare instances, in a small region. Recent work has begun to show that the ocean must eventually be studied in its entirety if it is ever to be understood. There are many physical and dynamical analogies between the oceans and atmosphere. Meteorologists have long recognized that the study of the atmosphere requires a global observation network. The existing observational base for the atmosphere is indeed truly global, combining ground-based radiosonde stations with satellite measurements. It is only the presence of this network that permits studies of large-scale dynamics, weather forecasts, and studies of climatic variability. Most of the fundamental scientific problems to be solved in understanding the dynamics of the world oceans require a similar global network.

Large-Scale Oceanic Circulation

The large-scale circulation of the ocean is driven directly and indirectly by the wind field, and by atmospheric heating at the equator and cooling near the poles. If there were no continents, the resulting flow would be dominated by strong zonal flows with a much weaker meridional convective component, similar to the atmosphere. Except for the Antarctic Circumpolar current, these tendencies for zonal systems are interrupted by continental boundaries, and instead we find ocean-basin scale gyrelike flows with a strong east-west asymmetry; relatively weak interior flows are returned in strong western boundary currents, a consequence of the spherical geometry of the rotating Earth. The spatial scales involved in the resulting circulation run from about 30 km up to the size of the largest ocean basins, about 10,000 km. A fundamental feature of the ocean is that it is vertically stratified, and thus the flow of water is a function of depth as well as geographic position. Superimposed on the time-averaged flows are a variety of time-dependent processes, which render the determination of the average extremely difficult and which also contribute dynamically to the large-scale mean distribution of properties. From the past decade of work, it is known that over great areas of the ocean, this variability (often called mesoscale variability or "eddies") can have energy levels one or more orders of magnitude greater than that of the mean flow.

Through turbulent eddy stresses, the existent variability is capable of generating time-averaged movement of various properties. These fields include passive tracers such as tritium, dynamically active tracers such as heat and salt, and dynamical quantities such as momentum and energy. Because different tracers can be transmitted and mixed differently, the large-scale, low-frequency circulation of the ocean cannot be defined uniquely through a knowledge of their distribution alone.

Knowledge of the internal pressure field permits calculation of horizontal currents. Internal pressure gradients arise both through horizontal changes in density and through changes in elevation of the sea-surface. Traditionally, the pressure field is computed from shipboard measurements of water density in which the sea-surface contribution is missing, a depth-independent factor that has not, until recently, been a directly measurable quantity. Instead, its effect on the geostrophically derived currents is usually inferred through some assumption about a depth at which the currents might vanish.

Measurement Problems

Historically, oceanographers have had to observe the world's oceans from a few slow, expensive ships. In more recent years, *in situ* measuring systems have been developed that are able to last for a year or longer, but these latter instruments are far too few and expensive to make measurements over the entire globe with adequate resolution.

Over the past 100 years of shipboard and *in situ* measurements, a gross quantitative picture of the large-scale circulation of the ocean has been acquired, based on the geostrophic relationship. There are two extremely serious problems with the resulting "classical" picture. First, because of the difficulty of sampling a global fluid from a ship, all observations have to be lumped together as though they were contemporaneous ("synoptic"). The problem is mitigated somewhat by the relatively high energies of low-frequency motions, but the smaller scales are dynamically and kinematically related to the larger scales. The other major problem, discussed earlier, is the lack of knowledge of the contribution to the pressure field made by the elevation of the sea surface. This depth-independent contribution is usually estimated on the basis of an educated guess that at some great depth in the ocean there is a level at which the absolute velocity vanishes, reducing the problem to the notorious "level-of-no-motion" controversy. Although some progress has been made recently in dealing with this problem, there is no generally accepted procedure that has been applied (or is applicable with existing data) to the global problem.

As a consequence of these difficulties, our existing knowledge of the global ocean circulation is at best semiqualitative. The lack of a quantitative picture is one of the greatest stumbling blocks to progress in understanding ocean circulation and its role in transporting heat and chemical substances and in ameliorating the effects of increases in atmospheric carbon dioxide.

It is possible that one could determine the absolute flow fields and time-averaged quantities by deploying modern recording current meters in the ocean. To measure circulation changes on spatial scales on the order of 100 km or less, however, would require an impossibly large number of spatially independent observations. Further, in most regions of the ocean the energy of the temporal variability exceeds that of the time-averaged variability by one or more orders of magnitude, with a structure requiring several years of data to obtain a stable, mean velocity.

The discovery of this intense eddy field, which dominates the velocity records, means that one must attempt to understand its character globally. As noted above, the time-dependent fields can have time-averaged effects through the nonlinear equations of motion. With existing equipment, a fragmentary picture of this global variability for short periods of time in restricted regions of the oceans has been obtained. To extend this beyond our present understanding, requires an integrated systems approach to ocean exploration.

OBSERVATIONAL REQUIREMENTS

The need for an improved understanding of the ocean's large-scale, low-frequency circulation from a global perspective has been emphasized. Measurements from space are ideally suited to this task, but are inherently constrained to observations at or near the sea surface. On this basis a well-founded observing system must utilize contemporaneous satellite and *in situ* measurements. Of prime importance are the measurements of sea-surface elevation and global wind stress from space with complementary measurements made within the ocean. The measurements of sea-surface elevation and wind stress are related and together determine the surface boundary conditions on the ocean. In principle at least, with these measurements it should be possible to solve numerically the dynamical equations to obtain the interior motions (using appropriate bottom boundary conditions) and to verify and improve the results obtained with *in situ* measurements of currents and subsurface properties.

TABLE A13. Observation Requirements: Physical Oceanography

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Sea surface topography	Ocean circulation: surface geostrophic velocity, feature location (fronts, eddies, rings). Also coupling of biological and physical ocean processes	Radar Altimeter: 10-20 day repeat track, orbit ≅ 65°, preferably non-sun-synchronous (if sun-sync, needs at least 3 satellites at different times of day). Also requires radiometer for moisture correction. Ref: TOPEX SWG
Significant wave height ($H_{1/3}$)	Wind, wave, and swell forecast	Radar altimeter; SAR
Sea surface temperature	Atmosphere/Ocean interaction feature location. Also coupling of biological and physical ocean processes	Same as TIROS AVHRR or Nimbus-7 SMMR, possibly HIRS-2 additional bands for aerosol removal
Sea surface stress/wind speed	Ocean circulation (wind driven part, ageostrophic motions, upwelling). Air sea interaction (flux determination by bulk formulae)	Scatterometer with automatic dealiasing, Ku band. One measurement within 50 km of any point up to $\pm 70°$ lat (or more) every 2 days. (See S-cubed report)
Surface wave directional spectra	Wave forecasts, wind forecasts, storm tracking	1) Research: SAR. Must cover global oceans. L-band works; we don't know how well C-X-Ku works 2) For improvement of scatterometer winds: Scanning short pulse altimeter flying simultaneously with scatterometer spectrum required at each scatt grid point

Direct measurement of ocean currents not only will serve to test models for the circulation based on sea-surface elevation and wind stress measurements, but also, will provide, because of the different spatial sampling and distribution of errors, independent information on the circulation as well. Such measurements have been made in limited regions with arrays of current meter moorings and by tracking from space acoustic signaling floats and surface buoys with attached drogues. However, a number of technical issues should be addressed before such tools are deployed in quantities useful for looking at global circulation. Measurement of subsurface currents and properties is extremely important for understanding their relationship to such surface measurements as elevation, wind stress, and temperature. A global program combining these subsurface measurements with those from satellites can best be accomplished by transmitting *in situ* data directly to one or more satellites, in effect creating a satellite-based oceanographic observing system.

Measurement of the sea-surface elevation from space will give, for the first time, the distribution of geostrophic surface currents, which, combined with traditional hydrographic sections, current meter and float data, will allow computation of the full four-dimensional current fields uncomplicated by the usual need to choose a reference level. Combining this first order kinematical description of the oceans with theoretical (both analytic and numeric) and process studies will ultimately provide the mechanism through which we will gain a more complete understanding of large scale, low frequency circulation and, in turn, its impact on significant societal concerns.

A complete program in ocean dynamics must therefore include a satellite-based oceanographic observing system, and continued support of theoretical and experimental studies. Combined, they will provide a first order kinematical description of the oceans and will ultimately be the mechanism through which we will gain significant insight into low frequency ocean circulation and the role it plays in controlling climate, fisheries productivity and pollutant cycling.

A summary of the satellite observational requirements for physical oceanography in the 1990s is given in Table A13.

POLAR GLACIOLOGY

Gordon deQ. Robin

SCIENTIFIC OBJECTIVES FOR THE 1990s

Two fields of research on polar ice sheets are likely to be of dominant interest during the 1990s. These are:

1. The role of polar ice sheets in the hydrological cycle ocean-atmosphere-ice sheets-oceans, especially in relation to climate change.

2. The study and interpretation of material in deep ice cores to provide improved knowledge of past climates and of the varying levels of atmospheric constituents such as CO_2, NO_x, SO_2, aerosols etc. over the past 200,000 years. Both topics require a better knowledge of ice dynamics.

The time constants for significant changes of the ice sheets are mostly long compared with atmospheric and oceanic processes and are similar to those of lithospheric changes and hence tend to have a stabilizing influence on climate. However, possible instabilities in the flow of ice sheets could have a drastic effect on sea level and climate on a time scale, estimated from inadequate knowledge to be from one to several centuries. Such instabilities would be due either to inherent characteristics of ice flow or to triggering by external changes of atmospheric temperature or precipitation. Approaches to this problem are firstly to improve our knowledge of ice dynamics to the point where reliable predictions can be made. To avoid relying completely on such predictions, the second approach is to monitor ice sheet behavior to give early warning of any changes of flow, form, temperature or mass budgets that point to the possible development of an instability.

Interpretation of ice core material requires satisfactory dating of the ice core at any depth and identification of the point at which the ice at any depth in the core was deposited (geographical coordinates and elevation). Although modeling of flow from ice sheet dynamics can help to answer these needs, the accuracy of dating tends to fall off rapidly before 10^4 years to an extent varying with location. New techniques may provide more direct and reliable dating of older ice core material while measurements of total gas content are already used to give some indication of the elevation of origin of ice. Identification of geographical point of origin of ice is however likely to remain a problem of modelling and hence of ice dynamics.

Major deficiencies in knowledge of Antarctic ice dynamics are:

1. A lack of understanding and observations of the interaction between the ice sheets and oceans, especially of melting and refreezing processes taking place beneath ice shelves and of the rate of melting of ice walls (the seaward front of the inland ice).
2. Lack of understanding of sliding processes at the base of ice sheets, of the role of water in these processes, and of subglacial water balance.
3. Improved ice drilling techniques are needed to survey and sample the deep ice, especially in East Antarctica.
4. Operational constraints on data acquisition due to the harsh environment of Antarctica. The same comments apply to Greenland except for 3 where improved drilling techniques in warmer ice than East Antarctica reached bedrock at 2057 m in 1981, near Dye 3 station.

Satellite observations can overcome some of these deficiencies. Logistically, satellite techniques provide a much more reliable, systematic and economic method of data collecting than airborne or surface operations, when satellite data is satisfactory.

OBSERVATIONAL REQUIREMENTS

Ice Sheets

Surface mapping is required for two purposes. The first is to improve our understanding of ice dynamics. The mean driving stress (τ) for ice sheets is given by $\tau = \rho g h \sin \sigma$ where the ice thickness (h) and the surface slope α refer to average values over horizontal distances at least an order of magnitude greater than the thickness while the other factors, the mean ice density (ρ) and gravity (g) vary little with position. To measure the mean slope over 30 km to better than 10% in central Antarctica with a mean slope as low as 0.002 radians requires measurements of surface elevation E to at least $\pm$ 3 m over a network of tracks spaced not more than 5 km apart. This accuracy was obtained by the Seasat radar altimeter with a footprint of 11 km diameter.

However, the limit to measurement of mean slope is mostly governed by the presence of surface undulations, commonly around ten or twenty meters in amplitude, but up to 60 m in amplitude at some locations. These are caused by additional stresses due to movement of ice over irregular bedrock terrain. The horizontal wavelength of these undulations on the cold Antarctic ice sheet is typically from two to perhaps ten times the ice thickness. Both theoretical and field evidence links the form of these undulations to the velocity of ice movement, to longitudinal stress gradients in the ice mass and to variations of basal shear stress. In the future, detailed knowledge of surface form of the ice sheet should make it possible to deduce the general character of bedrock morphology on a more detailed scale than is practicable from a network of airborne radio soundings of ice depths. To do this, a radar or laser altimeter should have a footprint of 1 km or less over central regions of the ice sheets and preferably down 0.1 km over the thin peripheral regions. Use of a satellite borne scanning radar altimeter with an accuracy of 3 m would provide excellent detail of the whole polar ice sheets.

Mapping of the coastal outline of the Antarctic ice sheet should preferably be done to an accuracy (horizontal) of 10 m, or to a minimum accuracy of 100 m depending on instruments that are available. These include Landsat imagery when reference points are visible on images, imaging radar systems (SAR), and altimeters that can locate coastal crossing points to 100 m or better.

Bedrock Mapping

The most effective measurements of ice depth may continue to come from aircraft soundings during the next two decades, but possible development of satellite ice depth sounding, though not promising, should be kept in mind. A 50 km square network of sounding over the major ice sheets by airborne equipment should be the aim, together with more detailed mapping of unusual bedrock features missed by the main depth sounding network but indicated by surface disturbances shown by altimetry or imagery. Such features could be studied in more detail from the air or surface. A more detailed network of flight lines will be needed in many coastal areas when surface contouring is complete.

Elevation Change

In addition to general mapping, more accurate radar altimetry is needed to determine longer term changes of thickness of both ice sheets and ice shelves. A relative accuracy between successive elevation measurements of $\pm$ 0.1 m is desirable if this can be achieved. Estimates of the rate of change of surface elevation based on other data (temperature profiles, strain data, total gas content of ice cores, isotopic data) suggest a present lowering of the ice surface of around 0.03 m yr^{-1} at Byrd Station, Antarctica, while a rise of around 0.03 m yr^{-1} is taking place at Camp Century, Greenland. The annual accumulation in the higher parts of East Antarctica is around 0.03 m yr^{-1} of ice, so an imbalance of 10 percent between accumulation and outflow would cause an elevation change of only .03 m in ten years, and so would take several decades to detect. However, in the more peripheral regions of Antarctica and over most of Greenland, accumulation is an order of magnitude higher and an accuracy of 0.1 m of elevation measurements would make it possible to detect slow long-term changes of ice thickness in about one decade. Any major change of thickness, such as that of 0.7 m yr^{-1} suggested by some Japanese results, could be detected in two or three years.

Ice Shelves, Ice Walls

On ice shelves existing satellite techniques can already supply much of the information needed for ice dynamics. Driving stresses on floating ice shelves are proportional to the weight of the ice above sea level, ($\bar{\rho}_i$ g E), where E is surface elevation and $\bar{\rho}_i$ the mean ice density above sea level. Alternately one can consider the stress as due to the equal but opposite buoyancy upthrust on ice below sea level $(\bar{\rho}_w - \bar{\rho}_{ib})gh_w$, where $\bar{\rho}_{ib}$ and $\bar{\rho}_w$ are mean densities of ice and sea water below sea level and h_w the ice depth below sea level. Ice shelves are almost horizontal and flat over large areas, and it should be possible to measure their surface elevation E to considerably better than $\pm$ 1 m accuracy, and so determine ice thickness and driving stresses. Horizontal motion of ice shelves is mostly from tens to many hundreds of meters per year, and hence can more readily be measured by satellite interrogation.

Changes of elevation with time at fixed markers travelling with the ice will give values of net accumulation and/or melting at the ice/water and ice/atmosphere interfaces combined after limited corrections for strain within the ice shelf are made. Changes of elevation with time at fixed geographical points will show whether the ice shelf is growing or diminishing.

A considerable amount of information on the behaviour of the Ross Ice Shelf has been gathered by many years of extensive measurements of surface strain, movement, accumulation, temperature etc., but information on bottom melting/accretion rates is almost non-existent. It appears that bottom melting on the Filchner-Ronne Ice Shelf may be much more extensive than on the Ross Ice Shelf. There may well be a considerable variation of behavior between different ice shelves. Satellite altimetry to check on budget states and satellite imagery to check on changes of seaward dimensions should make possible the surveillance of all significant ice shelves around Antarctica in a limited time on an economical basis.

The problem of advance or retreat into the ocean of grounded inland ice requires oceanographic observations to determine mass losses into the ocean on near vertical ice walls. Satellite imagery can provide extensive information on advance or retreat of these ice walls.

While satellite studies of the ice sheet/ice shelf-ocean interactions are complementary to oceanographic studies, the difficulties of drilling through ice shelves to do sub-ice oceanography are high. Satellite altimetric surveys should provide the most effective way of determining changes of ice shelf thickness and extent over wide areas during the 1990s. These studies are closely related to studies of the dynamics of ice sheets resting on bedrock below sea level, such as much of West Antarctica.

Some effects of ice sheet/ice shelf-ocean interactions will be seen through microwave and infrared imagery of the pack ice/ocean surface off the boundary of ice sheets/ice shelves using techniques described under discussions on pack ice.

Ice Dynamics

Other satellite measurements needed for ice dynamics of ice sheets and ice shelves are of surface accumulation/ablation rates, surface ice temperature distribution and the surface velocity field. The most accurate data will come from surface measurements, which could be collected from automatic instruments integrated into an Advanced Data Collection and Location System.

The most difficult measurement is of surface velocity since that is needed to 1 m yr^{-1} in central East Antarctica, 10 m yr^{-1} in coastal regions and on ice shelves. The most accurate measurements to date are by Doppler ranging to satellites from surface instruments (TRANSIT/TRANET), while development of retro-ranging satellite instruments would greatly reduce demands on logistics for surface observation points.

Quantitative measurements of mean surface temperatures and accumulation/ablation rates may be deduced from multi-spectral scanning in infrared and microwave radar bands if data interpretation advances sufficiently. Otherwise such multi-spectral data will give a useful qualitative indication of relative accumulation rates and temperatures.

Surface Flow Indicators

In addition to mapping surface contours and the outer boundaries of ice sheets, Landsat imagery has provided evidence of flowline directions through subtle variations shown in infrared imagery. Synthetic aperture radar coverage of ice sheets should provide further evidence of crevasse distribution over ice sheets when SIR-C is flown around 1989, and this also provides evidence of the pattern of ice flow.

Ice Sheet - Atmospheric Interaction

Apart from data on mass and energy balance needed as input to ice dynamic studies, the studies listed tend to fall in the sphere of atmospheric sciences. There is a need to find whether variations in ice core material, such as its content of CO_2, NO_x, SO_2 and aerosols, are proportional to changes of these constituents in the atmosphere, and if so in what region of the atmosphere. A series of atmospheric and falling/surface snow studies are needed to ensure that the very long time span of ice core records can be interpreted satisfactorily in relation to past atmospheric conditions. The satellite investigations that can help in this sphere are discussed mainly under Tropospheric Chemistry and Aeronomy.

Three further studies of potential importance in relation to ice sheet-atmosphere interaction should be mentioned since they are often neglected by dynamic meterologists because they are considered as local rather than global phenomena. These are katabatic winds, barrier winds and outbreaks of very large Antarctic icebergs.

Katabatic or downslope winds caused by gravitational drainage of cold air from the ice sheets over vast areas have been compared in their effects to the tropical trade winds. The cooling is due to loss of radiant heat from the surface of the ice sheet that cools a layer of air up to several hundred meters thick during winter months. This air drains off the ice sheets with velocities of tens of meters a second over long periods. The direct effects of katabatic winds on sea ice are mentioned as an item requiring further study in the section on sea ice.

Barrier winds are related to katabatic winds in that they are due to dynamic effects resulting from the piling up of cold air against a high mountain barrier. The best known case is in the Weddell Sea since when cold air is pushed against the eastern side of the Antarctic Peninsula, the dynamic forces produce southwest gale force winds along that side of the peninsula and over the adjacent western part of the Weddell Sea. Lack of agreement between modeling studies of Weddell Sea pack ice extent and the extent observed by satellite mentioned under the sea ice discussion is probably due to barrier winds.

It has been suggested for some years, that low temperatures in the Scotia Sea area of Antarctica are associated with the outbreak of very large icebergs, and this seems reasonable when the scale of an iceberg 150 km x 50 km by 250 m thick is considered. The ice therein is equal to the total snow accumulation over the whole Antarctic continent in one year, or more than the outflow of all the Siberian/Russian rivers into the Arctic Ocean in one year.

Conclusion

We can conclude by pointing out that many of the studies that should be undertaken in polar regions by Earth Observing System require similar instruments and techniques to those used elsewhere over oceans and inland surfaces. However to study polar regions two special requirements need to be met: Earth Observing System satellite(s) need to be in a sufficiently high inclination orbit to cover most of the polar regions. Instruments must also be adapted, often by relatively limited changes, to give satisfactory data over polar ice. The observational requirements for polar ice sheets in the 1990s are summarized in Table A14.

TABLE A14. Observation Requirements: Polar Ice Sheets

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Surface elevation	Ice dynamics	Line profile by laser altimeter accuracy 2 m or better ice sheet, 0.2 m ice shelves. Line spacing down to 1 km for single survey.
Surface elevation change	Ice dynamics, mass balance of ice shelves, measuring change	Radar altimeter monitoring at 20 km line spacing at 1 or 2 year intervals. Accuracy 0.1 m-1.0 m. More frequent if significant changes.
Ice boundaries (seaward)	Boundary velocity, measuring change	Ice shelf at 30 m accuracy by SAR at 2 year intervals. Inland ice walls to 30 m accuracy at 5 year intervals (SAR).
(inland)	Measuring change	To 10 m accuracy at 5 year intervals (SAR).
Accumulation rate and mean surface temperature	Ice dynamics	Areal average at 10 to 100 km spacing, for accumulation: 1 to 5 cm/year accuracy. Temperature: 100 km spacing, 1°C each year from microwave and IR radiometer and surface instruments (ADCLS).
Surface velocity strain rates	Ice dynamics and modelling	Point targets, interrogated by satellites to 1 m in position. 5 to 10 year intervals (laser retroranging).
Surface melting	Mass and energy balance	Microwave radiometry during summer. 1 to 3 day intervals near high sun time. Interrogate surface targets 10 cm/year (ADCLS).
Iceberg discharge	Variations within hydrological cycle	Catastrophic breakouts shown on imagery. Regional mean production to 10% yearly (SAR).

SEA ICE

Stephen F. Ackley

SCIENTIFIC OBJECTIVES FOR THE 1990s

Sea ice problems are by nature interdisciplinary and arise in relation to the role of sea ice in the climate system, in general. In particular, we wish to know how sea ice interacts with the ocean and the atmosphere. In a series of process-related experiments and by increased surveillance of sea ice covers by satellite systems (only since 1973) we have obtained some information on how ice covers respond to forcing by the ocean and atmosphere. In many cases, however, we are still in the basic observational state on sea ice, and are still learning for example where areas of persistent open water are within pack-ice areas, where regions of high deformation exist, where the velocities are particularly high, and so forth. In relation to atmospheric or oceanic sciences, these problems might be akin to knowing where regions of heavy rainfall are or where the major ocean current systems are located, or where upwelling occurs. Knowledge of where these analogous processes occur in sea ice regions of course says little about either what is controlling these processes or how they are interrelated to atmospheric and oceanic processes. A recent example of this problem was the observations during the mid-1970s of the Weddell Polynya, a large region of open water that formed for three years in succession inside the pack-ice in Antarctica. The polynya was observed to remain open thoughout the winter period (an observation only obtainable by satellite because of the remote nature of the location) and carried with it an immense capacity for air-mass transformation, for albedo feedback and for water mass formation processes. The details of these interactions and indeed why the polynya formed, why it persisted and why it disappeared are total unknowns. We have only some conjectures on its occurrence and even less information than that on its consequences.

A basic requirement is, therefore, a good observational data set that extends over periods of years. Information on features such as the Weddell Polynya illustrate our poor information base. We normally associate seasonal scales or shorter periods with sea ice phenomena, yet we now know interannual persistence is possible and can speculate that recurrence periods of the whole phenomena may be at decadal or longer time scales. Just as climate is the integration of weather, it appears sea ice phenomena result as a complex aggregation of forcings including some nonlinear reactions such as with the ice rheological properties occurring from the time scale of hours up to the decadal (or longer) scales, reflective of some of the phenomena recently observed. Understanding the processes involves conflicting requirements, on the one hand high time and space resolution, and on the other long time scales and "global" coverage in the polar regions.

As demonstrated, however, simple observation of the phenomena does not provide any real understanding of the processes involved without ancillary information on how the atmosphere or ocean are either driving the observed phenomenon (e.g., wind, currents, air temperatures) or how they are *responding* to the observed phenomenon (air-mass transformation, radiation reflection, cloud formation, ocean salinity/temperature/momentum changes). A goal of research on sea ice processes, therefore, is the development of coupled ice-ocean-atmosphere models, that through interactive processes, provide information comparable to "real" data sets. Some confidence in the basic physics underlying such models can, therefore, be obtained by these comparisons. They can then be used to project, or simulate in the long-term, future changes, including these feedbacks, of the Earth's climate and ocean and the role of the sea ice cover in those changes.

A series of particular problems follow that would provide the basis for such a "verification" data set and is amenable to satellite systems currently available or realizable over the next twenty years.

Sea Ice Roughness

A manifestation of the dynamic processes that form, along with thermodynamic growth, the basic structure of pack-ice is sea ice roughness. Continuous convergence and divergence processes modify this structure and cause pressure ridges, where blocks of ice are pushed up into adjacent floes. The deformation process modifies the ice mass balance, that is the total production determining the heat extraction from the atmosphere and salt flux into the ocean. Subsequent modificaton of the surface flow (affecting the dynamics of the ice) occurs and varies with the ice roughness. Mappings of regional variation in ice roughness, therefore, give insight into ice production regions, convergence regimes where stresses are high, and modification of the atmospheric and oceanic regimes. Large variability in the roughness in the Marginal Ice Zone is also a possible mechanism for momentum effects which are later manifested in oceanic and atmospheric dynamical effects such as ice edge jets, large scale heat transfer and dynamically induced ice melting.

Temperature and Wind Fields Over Sea Ice

The basic processes resulting in ice growth and motion are the growth induced by freezing temperatures and two ice dynamical effects, deformation and advection that are primarily driven by these atmospheric forcing fields. The observational base for these driving fields in pack-ice regions is very low with an only recently established buoy network in the Arctic Basin. Two years of buoy data (now terminated) were also gathered in the Antarctic over a limited region in the Weddell Sea. These limited measurements have indicated that significant discrepancies exist between these fields estimated from weather forecasts and actual conditions. In particular, the presence of the sea ice is not adequately considered in the construction of surface temperature records. Because of its inaccessibility and unusual character compared for example to ocean surfaces where radar scatterometer effects can provide substantial information on surface winds, sea ice surfaces present a more difficult sensing problem particularly in regard to wind fields. Until the present, space sensing has concentrated on determining sea ice response, such as SAR measurements of ice motion and passive microwave estimates of ice concentrations. In order to provide full coupling in models, however, not only the ice response but also the primary forcing fields have to be determined. By these measurements additional components of the ice motion provided by oceanic effects (for example, ocean currents and ocean heat flux) can be determined as residuals in the calculations once ice response, wind and temperature are taken out. At present, model determinations treat the effects in a highly parameterized way and provide only ambiguous information on the separate effects of, for example, atmospheric temperature increases and ocean heat flux changes on the sea ice response. Without this separation, feedback effects from the ice into these other fluids are even less amenable to determination, making the goal of fully coupling ice and ocean and atmospheric processes more elusive. These fields would also be of importance in understanding the atmosphere more clearly in polar regions. A major problem for example is the relation of ice processes to cloud formation in this area.

Ice-Albedo Variability

A fundamental problem in determining the radiation budget of the Earth's surface is the variability associated with snow and ice surfaces. Over the oceans, this feature is especially evident in the presence or absence of ice and is governed by the variability of ice concentration. Ice concentration effects are dominated by dynamical processes so ice motion effects are necessary to compute the albedo variations associated with ice presence or absence. Secondary, but important effects, are those associated with snow cover modification from melting/freezing processes so determination of the changes associated with wet or dry snow surfaces provide additional important albedo information. Snow and ice surfaces provide amplification effects by albedo changes and are, therefore, dramatically important somewhat disproportionately to their areal coverage because of this nonlinear effect. Their highly sensitive contribution dictates proportionately higher resolution in determining these effects. Feedback between surface modification, albedo and clouds are also crucial in characterizing the total radiation regime and, therefore, the net climatic effect induced by these snow and ice changes.

OBSERVATIONAL REQUIREMENTS

To address the scientific questions posed, several measurement capabilities are required. The acquisition of sea ice information has been significantly improved through two demonstrated satellite systems, passive microwave radiometry and synthetic aperture radar. These systems adequately define the sea ice characteristics desired. Within the context of the 1990s we may expect significant improvement in resolution (e.g., microwave radiometry from its present 10's of km spatial resolution would be more advantageously used if 1 km resolution could be achieved). Table A15 lists the major observables desired for sea ice definition and appropriate instrumentation for achieving these observations. In addition to the observables listed, which have demonstrated a system suitable for making that observation, a significant problem to be overcome is the data transmission to appropriate processing centers. Up to the present time, this has presented some difficulties, especially for ice observations in high southern latitudes because of the absence of down-link stations in the Southern Hemisphere. It is expected that communications satellites with data relay capability will alleviate this problem in the future but it should be addressed early in the design process to allow a truly "global" capability (both the Arctic and Antarctic) for observing sea ice.

As mentioned under the science problems, a major aspect of understanding sea ice interaction in the climate system is related to determining the magnitude of atmospheric and oceanic forcing fields on the ice cover. To date this problem has not been solved for ice covered regions, especially for wind, pressure, temperature and ocean current fields. In order to fully couple and verify sea-ice interaction into climate system models, these other observations must also be made in sea ice fields. They have been successfully made using automatic buoys and therefore a coexisting sea ice data buoy program with the expanded remote sensing of the ice cover would allow these questions to be adequately addressed. Sea-ice studies would then require extensive use of an Automatic Data Collection and Location System using data buoys, satellite data relay and satellite positioning.

TABLE A15. Observation Requirements: Sea Ice

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Boundary line position	Sea ice characteristics. Heat fluxes into atmosphere and ocean for meteorologic and oceanographic studies.	SAR or passive microwave radiometers. Daily, 5-20 km accuracy, radar altimeter.
Concentration percentage ice cover		To ≈ 10% for each type. SAR, microwave radiometry, radar altimeters, daily within 10% of area.
Albedo		Area average. Accuracy 0.02 at 25-100 km spacing, daily microwave radiometry.
Motion		Point displacement. 0.5 km/day. At 5-100 km spacing. Daily.
Ice type—ice thickness		SAR, Microwave radiometry, scatterometry, altimetric wave form, all in combination, 7 day intervals.
Ridging		SAR, scatterometry, or real aperture radar, 7 day intervals.
Leads		SAR, real aperature radar, Landsat daily.
Floe size distribution		SAR, Landsat, etc. To 10m floe size if possible (mean)—1 to 7 days in marginal zone.
Surface melting		Microwave radometry—over 100% ice cover when applicable daily in summer and in outer pack ice boundaries year-round.
Surface temperature	Forcing field information for sea ice response. Surface meteorological data for atmospheric forecasting and research.	IR and microwave radiometry—over 100% ice cover. Data buoys as tie points.
Wind velocity		Scatterometry—radar—over adjacent open oceans. Data buoys in pack ice regions.
Sea surface temperature		Over open oceans, 1°C accuracy.

TROPOSPHERIC SCIENCE

Conway B. Leovy

SCIENTIFIC OBJECTIVES FOR THE 1990s

The basic problem of the atmospheric sciences is prediction: How will weather, atmospheric composition, and climate evolve? The question can be applied to the "natural" evolution, or to the evolution as perturbed by various human influences, such as the addition of gases or particulates to the atmosphere. It can also be applied to the possible atmospheric evolution in response to essentially unpredictable perturbations, natural or human, for example: large volcanic eruptions, meteoritic impacts or nuclear war.

To focus the problem and to relate it to the specifics of low orbit satellite observations, it is useful to break it down according to time scale.

(i) Nowcasting

This is the problem of diagnosis and depiction of the detailed distribution of current weather, together with prediction of localized weather changes out to about 12 hours in the future. The emphasis is on hazardous weather elements such as tornadoes, hail, gusty winds and dense fog, but localized economically significant but less hazardous phenomena, such as pockets of severe frost, may also be included. This general problem is largely one of timely collection, display, dissemination, and interpretation of ground-based data, together with some appropriate model development. This will be an important area for research and technological development during the 1990s but geosynchronous satellites and communications satellites have a more important role to play than low polar orbiting satellites. Consequently, this problem area will not be considered further here.

(ii) Current forecasting

This is the familiar day-to-day forecasting based on timely assimilation of global surface, upper air, and satellite data and the use of highly sophisticated computer models for the dynamical forward extrapolation of data for periods ranging out as far as 10 days. More commonly, and more successfully these forecasts now extend to the 3-5 day range. Both geosynchronous and low polar orbiting sun-synchronous satellites play a major role in establishing the required data base, the so-called "operational" data base. Solutions to this problem are limited by the bounds of deterministic predictability. There is considerable room for narrowing the gap between the current state of the art and these fundamental predictability limitations by technical improvements in observations, data assimilation, and forecasting algorithms and forecasting practice, but the fundamental problems of predicting large-scale weather patterns on this time scale may be largely solved by the early 1990s, so that current forecasting does not now loom large as an area for major innovations in measurements by low polar orbiting satellites. There are some exceptions to this generalization which will be discussed in section 4.

(iii) Extended range forecasting

For time scales beyond about 3-5 days and extending out to the order of weeks to seasons, the fundamental limits on purely deterministic predictability, mentioned above, dictate that predictions must be framed in statistical terms. Relevant questions include the following: Are there characteristic spatial and temporal patterns of atmospheric anomalies from the long period climatological means? If so, what boundary condition anomalies such as occur in sea surface temperature (SST), snow cover, or surface potential evapotranspiration? To what extent are atmospheric anomaly patterns on these time scales purely internal to the behavior of the atmospheric circulation system itself? (For example, are there, even in a very approximate sense, multiple-equilibria with relatively rare transitions between them, as many simple models suggest?)

A few years ago, such questions were largely speculative, but in recent years there has been encouraging progress, and some indications of predictable components in the response of the atmosphere to anomalies in boundary conditions. Examples include quasi-global patterns of weather associated with the tropical SST variation known as "El Niño,"* and indications of a

*El Niño is an anomalous northern winter warming of the tropical Pacific surface waters from Peru westward to the dateline. It is associated to some degree with weakening of the trades in the subtropical Pacific, intensification of the jet stream and storminess over the extratropical mid-Pacific, anomalously warm temperatures in southwest Canada, and anomalously low temperatures in the southeastern United States. These atmospheric effects comprise part of a global pattern of atmospheric variability called the "Southern Oscillation."

connection between drought and surface potential evapotranspiration in Brazil, the Sahel, and the eastern U.S.

Though progress is encouraging, we are as yet very far from a complete solution to these problems. An important feature of the results that have been obtained is that they were not possible until a systematic high quality global data base had been accumulated in order to detect and map the anomaly patterns. A fundamental property of this data base is that it extends over a period of time significantly longer than that of any of the anomalous weather patterns contained in it.

Because of the global nature of the problem and the central role played by the interaction between the atmosphere and the surface, observations from satellites, and from low polar orbiting satellites in particular, are an important component of the necessary data base. As with other components of the data base needed for research on extended range forecasting, satellite observations must be systematic, global, and extend over a long period of time.

(iv) Climate prediction

At time scales of years, decades, or longer, the extended range prediction problem merges into the problem of climate change. Although many fascinating new issues appear at this time scale, probably the most urgent ones are those involving the potential impacts of human activities on the atmosphere. There are two observational aspects of this problem: monitoring of the concentrations and global distributions of substances whose concentrations can be influenced by human activities, and monitoring global weather patterns and their variations over time scales of years to decades.

A further division can be made between observational problems of the stratosphere and those of the troposphere. In the stratosphere, the climate problem centers around ozone, its variations, and aspects of the circulation regime or other constituents that can influence ozone. The techniques needed to measure the important constituents and circulation parameters from space are now relatively straightforward and low orbiting satellites will have a major role to play in any long term observational program.

In the troposphere, climate change is most likely to be effected by changes in the radiation balance brought about by changes in constituent concentrations (for example, the potential increase in the "greenhouse" effect which may be brought about by increases in the concentration of CO_2 or other infrared-active gases), or by changes in properties of the lower boundary which may alter either radiative or sensible and latent heat fluxes to the atmosphere. In contrast to the stratosphere, it is generally much harder to monitor the concentrations of the relevant constituents from space than it is to monitor them by means of *in situ* measurement techniques. Nevertheless, it is likely that the capability to monitor the global distributions of several important tropospheric trace gases will exist during the 1990s. The most interesting candidate gases are those having concentrations in the part per hundred million range, or greater, which are known or suspected to vary substantially over the globe. Low orbiting satellites also have a major continuing role in monitoring variations in the weather patterns which affect trace species concentrations on this long time scale.

Our knowledge of the radiation climatology of Earth and its relationship to surface and cloud cover conditions is still rudimentary. Advances in climate prediction will depend on the establishment of a long and quantitavely accurate baseline of data on the global distribution of radiation balance quantities at the top of the atmosphere and their relationship to surface properties, cloudiness and weather conditions. Improvements in satellite mesurements of radiation balance coupled with a program of surface radiation and ground truth measurements of surface properties will be needed.

OBSERVATIONAL REQUIREMENTS

The importance of continuity, modest upgrading, and quality control in an atmospheric research satellite program has been emphasized in Chapter II. Nevertheless, there are a number of possibilities for new initiatives, any one of which should be an important step for addressing the research problems outlined in the preceding section, and for which existing or foreseeable technology appears promising. Examples of such possible initiatives are described below, while the principal measurement needs for the 1990s are summarized in Table A16.

(a) Integrated hydrologic cycle measurements

The hydrologic cycle, and particularly the exchanges of moisture between the atmosphere and surface, appears to be an essential key to understanding certain problems of extended range prediction and climate. These include the problem of El Niño, and problems of drought in subtropical regions. Thus a research program geared toward assessing in an integrated measurement program the distribution of water transport by the atmosphere, the distributions of surface moisture content, surface potential evapotranspiration, snow cover, snow liquid water content, and diurnal surface temperature variations over continental areas is potentially very interesting. This would allow a two-pronged approach in which the local atmospheric column water balance is inferred both from direct measurements of atmospheric water balance and from surface measurements of evaporation and transport. The feasibility of direct assessment of water transport has already been demonstrated. Improvements would require an improved capability for measuring vertically resolved water vapor profiles and vertically resolved winds over the oceans. Such a program would also involve further studies of both active and passive micro-

TABLE A16. Observation Requirements: Atmospheric Extended Range Prediction & Climate

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
1(a) Atmospheric moisture distribution.	1. Define relationship of large-scale circulation to continental surface soil moisture/evapotranspiration.	1(a) Average over ~ 2° × 2° grid, minimum 3 levels below 500 mb, ~ ± 20%, global coverage, twice daily, continuing. *Instruments:* Passive microwave, thermal IR, near IR absorption. Lidar for high vertical resolution.
1(b) Soil moisture to depth ~1 m.		1(b) At least ~ 2° × 2° grid, ~ every two days over continents continuing. *Instruments:* Integrated combination including active and passive microwave and thermal IR. Requires extensive modeling and *in situ* investigations.
1(c) Evapotranspiration.		1(c) Regional, seasonal and interannual variations in plant moisture tension. Technique development needed, may involve joint use of synthetic aperture radar plus instruments for (b).
1(d) Winds (see item 4).		
2. Precip/evaporation over oceans.	2. Measure seasonal/interannual variations in oceanic moisture source.	2(a) Same as 1. (a) above, plus (b) passive microwave measurements of precip. 4 times daily, average over 2° × 2° grid. *(Ground truth a very severe problem).* Evaporation estimates require integrated combination including high resolution moisture profile (at least one data point within lowest 1/2 km, sea surface temperature and high resolution cloudiness. Lidar measurement of convective layer depth also useful.
3. Cloud top height, cloud top temperature, cloud albedo, cloud thickness and/or liquid water content.	3. Relationships between seasonal and interannual variation. Energy budget, the cloud factors which influence energy budget, and surface energy source/sink and atmospheric circulation structure (i.e.: "cloud climate problem").	3(a) Improved data handling to give at least coarse statistical properties on 2° × 2° grid, 4 times daily, global, continuing. (b) Cloud top height sensor (± 1/2 km.). (c) Liq. water content, 2° × 2° spatial resolution, ~ 10 gradations between cloud free and heavy tropical clouds on a linear scale. *Severe ground truth problem.* (d) At least current state of the art visible and near IR sensors. (e) Broad band solar and thermal radiation budget measurements at least equivalent to those on ERBE.

TABLE A16. (Continued) Observation Requirements: Atmospheric Extended Range Prediction & Climate

4. Measure tropical winds.	4. Define tropical circulation.	4. Measure at $\gtrsim 3$ levels, better than ~ 100 km squares, $\sim \pm 2$ m/sec. accuracy, at least 4 times daily, continuing. Instrument: Doppler lidar.
5(a) Winds/temperature (b) ozone (c) other reservoir gases: HNO_3, HCl, H_2O, NO_2, etc., in the 15-90 km range.	5. Interannual variations and long term trends in the middle atmosphere.	5. See table entries in middle atmosphere science.
6. Ocean surface conditions	6. Relationship between ocean circulation and atmospheric thermal and mechanical forcing.	6. See physical oceanography, items 3 and 4.

wave techniques for surface liquid water, snow, and vegetation measurements, multi-channel visible and near IR radiometry, thermal IR surface temperature measurements, and improvements in both satellite and ground-based methods of characterizing the global distributions of wind, temperature, cloud and precipitation.

(b) Cloud parameter characterization

Improved understanding of the interaction between clouds, with their concomitant distributions of both latent heating and radiative heating perturbations, and other elements of the atmospheric heat engine has long been recognized as an important key to both the extended range forecasting problem and the climate problem. More detailed quantitative data are needed on cloud cover distributions, cloud albedos, cloud thicknesses and/or mass contents (liquid and/or solid), cloud top heights, and cloud top temperatures. The latter two items are often considered together because of their close relationship, but it is important to distinguish them because many clouds have emissivities less than one (put another way: The level of unit optical depth is often quite different at visible and thermal infrared wave-lengths). Many of these goals might be met by improved handling of data from existing sensors.

Ideally, one might like to have a few statistical moments of the distributions of cloud albedo, cloud top height, and cloud top temperature together with a measure of cloud thickness and/or mass content in each element of a global spatial grid of the order of 2° latitude square, and with time resolution at least capable of resolving semi-diurnal variations. New techniques which should be pursued to achieve these goals include: improvement in data handling and processing including on-board data compression, improvements in the techniques of assessment of cloud mass content (probably using microwave techniques) including the "ground truth" validation of space measurements, and development of passive or active techniques for determination of cloud top height. Improved characterization of clouds should proceed hand-in-hand with improved characterization of the top-of-atmosphere radiation balance.

Improvements in the assessment of cloud properties may have some important spin-offs. They could lead to improved satellite determination of temperature and constituent profiles, and improved retrieval of sea surface temperature. Thus they could eventually feed back to the current forecasting problem.

(c) Air sea interaction measurements

It is now technically feasible to determine the simultaneous distributions of sea surface topography (from which the barotropic component of the current can be determined), the surface stress, and the sea surface temperature (with an accuracy of at least 1°C). Determination of the simultaneous distribution of these fields, together with measurement of "weather" variables, and radiation balance quantities has very exciting potential for both the extended range forecasting and climate problems. A research program in this area involving low polar orbiting satellites is a promising potential area for cooperation between oceanographers and meteorologists. Several of the elements of such a program are also elements of (a) and (b) above.

(d) Tropical winds

There is evidence that an important limitation on the accuracy of current forecasts is imprecise knowledge or assimilation of tropical winds. These are now determined to within a vector accuracy of the order of 5 m/s at two levels: approximately 950 mb and approximately 300 mb from cloud drifts. More accuracy, precision in vertical location and vertical resolution might help the current forecast problem and could also provide a more useful data base for both the extended range forecast and climate problems. It is also an important component of a global hydrologic cycle program. Thus, it would be well worth exploring the feasibility of obtaining tropical winds from space directly. Such measurements might supplement or complement the cloud drift winds now being obtained, and might also reduce possible biases inherent in the cloud drift winds. Studies in this area should carefully consider the detailed ways in which new tropical wind data could be assimilated into analysis and forecasting systems since the assimilation of these winds poses special problems.

(e) Tropospheric gaseous species

The global distributions of a number of minor gas species may be accessible to satellite measurement systems employing gas correlation spectrometry and/or lidar techniques in the 1990s. Such global measurements could provide invaluable insight into the source, sink, and transport mechanisms influencing the concentrations of these gases. Some of the more likely candidate gases are CO, CH_4, NH_2, and SO_2, although other gases may also be possible. Measurements of global distributions of any of these gases should be closely integrated with conventional meteorology measurements in order to assess transports.

MIDDLE ATMOSPHERE SCIENCE

John C. Gille

SCIENTIFIC OBJECTIVES FOR THE 1990s

In recent years the term "middle atmosphere" has been applied to the region between the top of the troposphere (8-15 km altitude) and the base of the thermosphere (~80 km). This is a region in which radiative, photochemical and dynamical processes are tightly coupled. The middle atmosphere is also closely coupled with the underlying and overlying atmospheric regions, through exchanges of mass, momentum, energy, and chemical constituents. Thus, not only does an understanding of the middle atmosphere require a coordinated study of all the processes operating, but it must be seen in relationship to adjacent atmospheric layers.

In addition to the scientific challenge of understanding the middle atmosphere, it is of critical importance to mankind. Most of the atmospheric ozone, which shields the biosphere from damaging UV radiation, is in this part of the atmosphere. The middle atmosphere also affects the surface climate through radiative and dynamical linkages. Thus, it is necessary to understand middle atmospheric processes, observe its long term changes and trends, determine their causes, and develop reliable tools for predicting the future evolution of this region.

1. Understanding Radiative, Chemical and Dynamical Processes in the Middle Atmosphere

One of the major discoveries in the 1970s was that the ozone concentration, which is of the order of parts-per-million, can be controlled by gases present in only parts-per-billion concentration or less. These include notably the active nitrogen, hydrogen and chlorine species. At present, the major features of middle atmospheric chemistry are believed to be understood. However, important new compounds and processes have emerged with regularity over the last several years, suggesting that we can not with confidence assume that we have the final answer.

Photochemistry in the middle atmosphere can be thought of as beginning with the transport of source molecules for the chemical families of nitrogen, hydrogen, chlorine, etc., from the troposphere into the stratosphere. There they are transformed by photolysis and chemical reactions into highly reactive radical species. These are eventually transformed into sink species, in which form they are removed. Part of the time the radicals are combined in temporary reservoir species; these react slowly, and often link different families.

The action of catalytic cycles involving these species can change the concentrations of those gases which interact with the radiation field, modifying patterns of heating, and thus of atmospheric motions. The winds, in turn, modify the distributions of the reacting species.

A start has been made on understanding these processes and couplings. Large gaps in our knowledge remain. A program to observe as many of the chemical, dynamical and radiative variables simultaneously over at least an 18-24 month period will be required to understand the linkages among these processes.

2. Long Term Evolution of Middle Atmosphere Chemistry

Even with a much improved understanding of the mechanisms, large numbers of problems will still remain. These are concerned with the long-term changes in the atmosphere, including those due to anthropogenic causes, year-to-year variations in the atmosphere, and the response of the atmosphere to the solar cycle.

It is impossible to completely separate chemical from dynamical processes, because they are closely coupled through transports and radiative effects. However, for convenience of discussion, we will discuss them individually. One of the first requirements is for long-term measurements of the vertical and horizontal distribution of ozone. Ozone occupies a special place in middle atmospheric chemistry because of its role in protecting the Earth's surface from ultraviolet radiation which is damaging to biological organisms. In the stratosphere it is important because it provides the major source of atmospheric heating. Because this heating is not uniform on pressure surfaces, it serves to drive atmospheric motions.

For progress on understanding the long-term chemical evolution of the atmosphere, it will be necessary to make measurements from space of all key long-lived major constituents, including those which are sources of radicals, radicals themselves, and the sink molecules which remove the active species from the stratosphere. It will be necessary to measure these species over a period of at least one solar cycle (11 years) to define the year-to-year, or interannual, variability, and to separate the effects of various factors on the concentrations of the species of interest. Among the factors which will be necessary to consider, and therefore to measure, is the temperature, which is strongly influenced by the concentrations of CO_2. This is now increasing at a significant rate per year, and should also be measured. In addition, measurements of the spectral distribution of the solar flux and its variability will be needed over the same time period.

It is not possible to measure all the quantities which are desired. Models must be used to calculate the quantities which cannot be measured, based on the concentrations of those which can, and other physical variables. The goals must be constant refinement of our understanding of the chemical processes, improvement in our capabilities to monitor long-term changes in the middle atmosphere, determination of the causes of such changes, and prediction of the long-term response to natural and anthropogenic variations.

3. The Interannual Variability of Middle Atmospheric Dynamics and Transports

At least three studies have shown that four-year averages of atmospheric quantities during the winter yield different results if different four-year periods are taken, i.e., the averages are not stable. For a multiyear period it will be necessary to obtain measurements of the temperature, from which the winds in balance with the atmospheric mass fields can be derived, plus direct measurements of the winds, in order to understand the interannual variability, and the way that the stratospheric motions affect tropospheric weather and climate. Long-term measurements will also be necessary to demonstrate the response of the middle atmospheric motions to changes in composition.

As noted above, the motions also interact with the composition, leading to important coupling between the chemistry and the motion fields. The role of transports in maintaining the budgets of stratospheric species still needs to be quantitatively observed over a multiyear period, and understood through model simulations.

Once again, it will be necessary to merge measurements and models to get better values for those quantities which are not measured directly, including such ageostrophic components as the vertical motions. These can be used in the study of troposphere-stratosphere exchange, which is one of the critical links in stratospheric chemistry, as well as interactions between the mesosphere and thermosphere.

4. Chemistry, Dynamics and Energetics of the Upper Mesosphere and Lower Thermosphere

This extremely interesting and complex region is the transition from the underlying atmospheric regions in which the major gases are uniformly mixed, in local thermodynamic equilibrium (LTE), and electrically neutral, to the overlying regions which are diffusively separated, not in LTE, and ionized. The direct response of the underlying layers to solar changes appears to be long, while that of the upper layers is extremely rapid.

Photochemistry by energetic UV radiation is very important at these levels. Most polyatomic molecules have been dissociated before reaching this altitude, but CO_2, H_2O, O_3 and CO are present. Other species are being formed, such as NO and O, as well as numerous ions, but the details are very uncertain.

A single temperature cannot describe processes in this part of the atmosphere, where energy levels are not necessarily populated according to a Boltzman distribution. It is necessary to know the kinetic, rotational and vibrational temperatures at these levels to describe processes such as the absorption and emission by the 15 μm and 4.3 μm infrared active bands of CO_2. Sunlight absorbed by these molecules may be immediately re-emitted (scattered), or emitted after a series of collisional processes by another molecule at a different frequency.

Other emission features play a role in the energetics of this part of the atmosphere. Under quiet conditions these include CO_2 (2.7 μm, 4.3 μm, OH (1.6-4 μm), and O_2, ($^1\Delta g$) (1.27 μm, 1.56 μm).

Under conditions of auroral excitation, large amounts of NO are formed. This radiates intensity at 5.3 μm and 2.8 μm, with large intensity; these emissions have rapid space and time variations, especially during magnetic substorms and auroral disturbances.

Previously, this region had not been observable from space, and has been referred to as "the ignorosphere." Now, technology is available to allow detailed measurements of this region, which is the last major unexplored region between the Earth's surface and the surface of the Sun. An understanding of solar-terrestrial influences requires that this region be understood.

OBSERVATIONAL REQUIREMENTS

1. Measurements for Understanding Middle Atmospheric Processes

The requirements are for an intensive but not necessarily long period, in which all the important species are measured, along with temperature and photochemical inputs. Measurements are needed for O_3; the source gases H_2O, CH_4, N_2O, CF_2Cl_2, and $CFCl_3$; the radicals NO, NO_2, ClO and OH or HO_2 if possible; the sink species HNO_3 and HCl; and if possible the temporary reservoirs $ClONO_2$, HO_2NO_2, HOCl, and N_2O_5. Accompanying measurements of temperature, winds, the solar UV spectrum and charged particle inputs are also needed. The observations should extend over at least two northern winters, and preferably over at least two full years. The planned UARS program should provide the observations required, and the basis for a detailed understanding of the crucial processes.

2. Measurements Related to the Long Term Evolution of Middle Atmosphere Chemistry

Ozone occupies a special role in middle atmospheric chemistry because of its role in protecting the Earth's surface from ultraviolet radiation which is harmful to biological organisms. In the stratosphere ozone also provides a major source of atmospheric heating. Measurements of total ozone and ozone profiles are required. The total ozone should be accurate to at least 5%. However, since the main thrust will be a search for trends and variations, long-term stability is even more important. This stability is with respect to time for a single instrument, and between instruments if it is necessary to change from one to another over a long period. Similarly, the precision of an individual measurement must be high, in order for trends to be seen clearly.

For the vertical profiles, the altitude range should extend from as low as possible, but at least from the tropopause, up to .1 mb (64 km), and preferably to 80 or 90 km. Because such measurements are very important for checking theoretical predictions, accuracy should be 10% or better. Again, because of the desire to look for long-term trends, long-term stability and high precision are required.

If changes in ozone are observed, it will be necessary to determine their cause. For this reason, long-term measurements of a set of key constituents will be required, with special emphasis on those molecules which are the sources and sinks of the radicals which are responsible for the catalytic destruction of ozone. The radicals themselves should also be measured where this is convenient. Concerning the source molecules, for the nitrogen compounds the requirement is to measure N_2O, and, if possible, lower stratospheric NO which may result from anthropogenic emissions. For the hydrogen compounds, the requirements are to measure H_2O and CH_4, while for the chlorine compounds it is necessary to measure CF_2Cl_2, $CFCl_3$, and if possible CCl_4, CH_3Cl and CH_3CCl_3. These should be measured from the tropopause until their concentration drops below significant levels, which will vary with the species.

For the sink molecules, the nitrogen and chlorine species measurements of HNO_3 and HCl are needed. In addition, to distinguish between natural and anthropic chlorine sources, measurements of HF would be desirable. Finally, measurements of HBr could help monitor any change in its role in ozone destruction.

Among radical species, measurements of NO or NO_2, as the most active nitrogen compounds, would be desirable, as would measurements of ClO and OH or HO_2.

The altitude requirements for the sinks and radicals are the same as those specified for the sources.

In addition to the species themselves, additional measurements required are the concentrations of CO_2, which is important for its role in the heat balances of the surface. CO_2 also affects the middle atmospheric temperature, which in turn controls the rates of many important chemical reactions.

Finally, it will be necessary to obtain long-term observations of the absolute values of the solar irradiance above the atmosphere, its spectral distribution, and the varibility in the different spectral intervals as a function of time.

it should be pointed out that many of the trace gas measurements are also of interest for climate studies.

3. Measurements Related to Interannual Variability of the Middle Atmospheric Dynamics and Transports

As noted previously, there appears to be significant interannual atmospheric variability over periods longer than 4 years. In addition, there are significant long-term variations, including the quasi-biennial oscillation which is seen in tropical dynamics (and mid-latitude ozone distributions).

It is necessary to obtain measurements of the vertical distribution of temperature from the tropopause to the upper mesosphere, with accuracy and precision which allow geostrophic or gradient winds to be determined. In addition, there are significant long term variations, including the quasi-biennial oscillation which is seen in tropical dynamics (and mid-latitude ozone distributions).

It is necessary to obtain measurements of the vertical distribution of temperature from the tropopause to the upper mesosphere, with accuracy and precision which allow geostrophic or gradient winds to be determined. In addition, it would be desirable to have direct measurements of the winds to provide information at low latitudes, or above 1 mb where ageostrophic components are expected to be large. Furthermore, if the direct winds are sufficiently accurate, they can be integrated over a long period of time to provide a measure of the mean meridional circulation, which is not in geostrophic balance. This is extremely important in the maintenance of the balances of heat, momentum, energy and trace gas distributions. For these purposes, temperatures should be measured to 1 K, from 15-80 km, and wind to about 3 m/s, especially in the upper levels.

4. Measurements related to the Chemistry, Dynamics, and Energetics of the Upper Mesosphere and Lower Thermosphere

Measurements of the composition, winds, and a wide variety of emission features which play a role in the energetics of this part of the atmosphere will be necessary. Composition, including the abundance of O_3, H_2O, CO_2, and CO, NO and O may be determined by measurement of the infrared absorption and emission spectra, ultra-violet spectra, and microwave radiometry.

Because of non-LTE effects, temperatures cannot be determined from the broad band measurement of the infrared emission by atmospheric bands. Again, high resolution IR spectra may be used to provide vibrational and rotational temperatures. Measurements of line widths with a Fabry-Perot interferometer will allow a determination of the kinetic temperature.

Direct measurements of the winds are required to understand the dynamics of this region, including the temporal and spatial scales involved, and the response of the motions to various perturbations.

Finally, spectrometer or narrow band radiometer measurements are required to measure the outgoing energy and its spatial variation. The emission features include, under quiet conditions, CO_2 (2.7 and 4.3 μm), OH (1.6-4 μm), and O_2 ($^1\Delta g$) (.27 μm, 1.56 μm).

Under conditions of auroral excitation, NO emissions at 2.8 and 5.3 μm also need to be measured. All these emissions have rapid space and time variations, especially during magnetic substorms and auroral disturbances, which suggests that a quantitative imaging-type system may be required for some purposes. Other problems will require accurate radiometric measurement of the outgoing signal.

The observational requirements for the middle atmosphere are summarized in Table A17.

TABLE A17. Observation Requirements: Middle Atmosphere Science

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Atmospheric Temperature	Chemistry, Dynamics, Transports, Energetics	Surface—150 km Resolution ~1/2 scale height Accuracy $\leq \pm$ 2°K 0-80 km $\leq \pm$ 5°K 80-120 km $\leq \pm$ 10°K 120-150 km Precision—1/2—Accuracy
Winds	Dynamics, Transports	Surface → 50 km, ± 20° LAT ± 3m/s > 50 km − 150 ± 10 m/sec
Constituent Concentrations Source Molecules O_3, N_2O, CH_4, $CFCl_3$, CF_2Cl_2, H_2O Reservoir Molecules HCl, HNO_3, H_2O_2, HNO_4, $ClONO_2$ Radicals ClO, NO, NO_2, OH, HO_2	Chemistry, Transports	Various Altitudes ~ 10% Accuracy Necessary ~ 5% Desirable Precision ~ 1/2 Accuracy 1/2 scale height vertical resolution
Emission Features $O^2(^1\Delta g)$, OH Bands 1-4 μm NO (2.8 μm, 5.3 μm) CO_2 (4.3 μm, 10.4 μm)	Energetics of Upper Mesosphere—Lower Thermosphere (NON-LTE Excitation)	1/2 scale height vertical Resolution, Spatial Distribution Desirable Accuracy ~ 25% Precision ~ 10%

AERONOMY

Paul Hays

SCIENTIFIC OBJECTIVES FOR THE 1990s

The upper atmosphere has traditionally been divided into a set of ordered regions extending from the ground to above the sensible atmosphere and these regions have been treated as if they were nearly independent. It is, however, clear that this view is misleading and the dynamics, chemistry and material balance of the atmosphere are strongly coupled with each other and with altitude. Furthermore, at least in the upper regions of the atmosphere there is obvious and strong dependence of the atmosphere on solar activity and resulting geomagnetic storms. These solar-terrestrial relationships have not been traced through clear causal links to all regions of the atmosphere. The central theme of Aeronomy in the 1990 period will be the formulation of a coupled global view of the upper atmosphere as an integral extension of the lower regions.

Photochemistry and Transport

The thermosphere and upper mesosphere are the scene of the most violent chemistry occuring in the Earth's atmosphere. All molecular species are subject to dissociation and ionization in these regions, leading to the creation of large resevoirs of highly reactive radicals and chemically active species. The upper mesosphere is a region in which hydrogen compounds such as the hydroxyl radical strongly influence the chemistry. The present knowledge of this region and its chemistry is at best sketchy and this situation will not change in the next ten years. Some of these active compounds created both in the mesosphere and lower thermosphere are transported downward in the atmosphere, thus influencing the chemistry at these lower altitudes. There is evidence that in the polar night nitric oxide (NO) formed by the aurora is transported to lower altitudes thus perturbing the entire atmosphere. Recent measurements made on ice cores suggest that some of this nitric oxide eventually is deposited as nitrate in the polar ice caps. This nitrate shows a correlation with solar activity indicating its thermospheric origin. This problem is mentioned as an illustrative example of the importance of understanding the high atmosphere as a source of minor constituents which perturb the more dense atmosphere below. A related area of investigation is transport of these same minor species in company with certain major species within the thermosphere by the wind systems at high altitudes.

Atmospheric Dynamics

The dynamics of the thermosphere and upper mesosphere are beginning to be understood in sufficient detail that we can identify the problems for the future. The motion of the high thermosphere has been shown to be driven by a combination of the global solar EUV energy input and the more local, high latitude sources of energy and momentum from magnetospheric fields and currents. The temporal and spatial variability of these energy sources remains to be quantified during the 1990 period. In particular there are important questions about the distribution and temporal variation in the magnetospheric energy input to the neutral atmosphere. The dynamics in the upper mesosphere and lower thermosphere differ considerably from those at F-region heights. This is due to the changing optical depth in this region at EUV wavelengths, the upward propagation of tides from the lower atmosphere, the rotation of ion drifts from the E x B to the Pederson direction, the decrease in the effectiveness of ion drag and the effect of NO heating and cooling. The problems of the 1990s here will center on the climatology within these regions. Emphasis will be given to the use of optical signatures of dynamical processes to discern the influence of solar and magnetic storm activity on the motions of the atmosphere in this transition region. The dynamic response of this lower region directly influences the minor constituent transport discussed in the last section.

Atmospheric Electrical Circuit

The upper atmosphere plays a very important role in the global electrical circuit, closing the current loop from the top of the thunderstorm charging generator with the global fair weather current systems. This circuit is very strongly perturbed in the polar regions by the cross polar cap potential pattern which is produced by the magnetospheric generator. These polar fields are observed directly on the surface of the Earth at mid to high latitudes and are the one obvious solar-terrestrial effect which we sense at sea level. Two areas will be of interest to us in the 1990s, these being the thunderstorm charging process and the polar region potential pattern driven from the magnetosphere. Both of these problems areas represent large uncertainties in our understanding of fundamental atmospheric processes.

Energy Budget

The lower thermosphere and mesosphere are regions in which the energy budget is not well quantified. This is due in part to the lack of observations in these regions and to the lack of a global perspective of the radiative coupling between and out of regions of the atmosphere. The mechanical flux of energy in the form of gravity waves and turbulence is poorly understood. These processes may well be examined by imaging at ultraviolet and infrared wavelengths. Here again reliance will be placed on indirect measurements based on previous detailed *in situ* studies to uncover, in this case, the global morphology of the energy sources which drive the atmosphere.

OBSERVATIONAL REQUIREMENTS

Several issues have surfaced in the process of discussion of the aeronomical problems of the 1990s and the concept of a space based geophysical system. These center on the need to supplement the remote sensing measurements which can be made from a large sized platform or spacecraft. The principal observational requirements for aeronomy in the 1990s are summarized in Table A18.

In situ Measurement Capability

A clear need is seen by the aeronomical community for smaller and cleaner spacecraft from which to measure the electric fields, composition of the neutral and ion species, the large scale currents and the atmospheric motion which occur locally. These small spacecraft should be integrated with the larger system stations and probably will station keep with the larger spacecraft. The lower altitudes could well be examined by using the 'tether' satellite concept based from one or more of the large 'mother' spacecraft. The lower altitude tethered satellite could be used to survey a series of lower altitude orbits, acting both as ground truth for the more indirect remote images and directly as a source of information on this difficult region.

Complementary Orbits

There is a need to have a global view of the high atmosphere and the energy inputs to that region. This implies that the basic orbits used by the larger prime spacecrafts will not be suitable for all remote sensing instruments. In particular there is a need for high orbiting smaller craft which will carry UV imaging devices which will quantify the polar inputs of energy and will track species such as ozone, atomic oxygen, atomic hydrogen, as well as molecular oxygen and nitrogen. A strong case can also be made for keeping a magnetosphere monitor station in high orbit to track the fluctuations in the particle energy inputs. Possibly, these two functions could be satisfied from the same small orbiter placed in a high polar orbit.

Sounding Rockets

The atmosphere between 40 and 120 km can only be sampled directly from sounding rocket probes. There is and will be a continuing need to carryout flights for verification of remote sensors which are carried on the large spacecraft, flights to develop instrumentation, and flights to carryout point intensive experiments and discrete studies. These simple vehicles are a very cost effective way to supplement the global data which will be collected from the remote sensing devices flown on the large spacecraft.

Ground System Service

There is a need to service remote ground stations which are supporting the basic geophysical mission of the satellite system. This type of function would involve the reception of data from the ground station and the transmission of commands to the ground station. It may not be necessary for this function to be carried out from the prime spacecraft, but the data should reach the central data storage facility at the same time as the data from the space system.

TABLE A18. Observation Requirements: Aeronomy

OBSERVATION	SCIENCE PROBLEM	MEASUREMENT CHARACTERISTICS
Thermospheric Winds	Atmospheric Dynamics, Minor Constituent Transport	Visible High Resolution Spectroscopy, 5000-8000 Å, $\Delta\lambda \sim$ 0.01Å Fabry-Perot Interferometer $\vec{V}_N$ (100-500 km)
Mesospheric Winds	Atmospheric Dynamics, Minor Constituent Transport	Visible H.R. Spectroscopy, Atmospheric "A" band with multiple Etalon Fabry-Perot, $\vec{V}_N$ (60-120 km)
Statospheric Winds	Atmospheric Dynamics, Minor Constituent Transport	Visible H. R. Spectroscopy, Atmospheric "B" band with multiple Etalon Fabry-Perot, $\vec{V}_N$ (15-50 km)
Tropospheric Winds	Atmospheric Dynamics, Minor Constituent Transport	Doppler Lidar using either visible or IR laser depending on cost studies, $\vec{V}_N$ (0-15 km)
Mesosphere-Thermosphere Minor Constituents	Transport of Reactive Gases between Regions in Atmosphere	1. Limb scanning multiple wavelength Photometric Low Res. 100-15,000 Å selected regions, n_i. 2. Global imaging from high altitude, $N_i = {}_z\int_o^a n_i d$; 100-3000 Å 10Å selected. 3. Cryogenic limb scanning spectrometer covering range 2.5-16 µm. 4. Cryogenic limb scanning radiometer
Thermospheric Composition	Thermodynamics of High Mesosphere	*In situ* mass spectroscopy, Ion and neutral n_i, n_i^+
Electric Fields	Global Electrical Circuit	Ion Drift Meter & Retarding Potential Analyzer $\vec{V}_i$, $\vec{E}_i$, T_i
High Thermospheric Motion	Thermospheric Dynamics	Neutral Drift Meter and RPA. $\vec{V}_N$, T_N
Energetic Diagnostics	Thermospheric Heating Mesopheric Chemistry	Near IR limb scanning. Radiometer for O_2, OH, NO, emission features
Particle Energy Input	Thermospheric Heating, Mesospheric Chemistry	1.0 eV – 100 keV e^-, H^+ Particle Spectra, F_e, F_{H^+}
Thermal Plasma	Ionospheric Development and Perturbations	Thermal plasma density and energetics, n_e, T_e

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15. Supplementary Notes

Science and Mission Requirements Working Group for the Earth Observing System

16. Abstract

The Earth Observing System (EOS) is a planned NASA program, which will carry out multidisciplinary Earth science studies employing a variety of remote sensing techniques in the 1990's, as a prime mission, using the Space Station polar platform. It's primary goal is the generation of long term Earth science data sets of measurements and processes in the areas of agriculture, forestry, geology, hydrology, oceanography, snow and ice, troposphere and upper atmospheric chemistry, radiation and dynamics pertaining to global studies of Earth as a system, emphasizing the interactions and couplings of the atmosphere-ocean-land-cryosphere system. These results will provide the information needed to qualify our understanding of the global hydrological cycle, global biogeochemical cycles and global climate processes.

This report provides the science rationale, recommended observational needs, the broad system configuration and a recommended implementation strategy to achieve the stated mission goals. The report is one volume of a proposed five volume set constituting the Phase A report as the Earth Observing System (EOS).

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